UNIVERSITY OF NEVADA-RENO

A RESERVOIR-ROUTING MODEL CALIBRATION METHOD RELATING STORAGE ELEMENTS TO BASIN GEOMORPHOLOGY FOR PEAK RUNOFF PREDICTION FROM EXTREME SUMMER STORM EVENTS IN UNGAGED ARID WATERSHEDS

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by

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ABSTRACT

A study of synthetic geomorphologic and hydrologic data has been used to determine relationships between the storage constants of a parametric storage-routing model and influential peak runoff producing parameters, allowing the direct synthesis of peak runoff hydrographs from extreme summer storm rainfall patterns.

The size and drainage configurations of watershed subunit cells, termed unit areas, govern the degree of influence of dominant hydrologic parameters on simulated peak flow. As unit area size increases, channel slope and overland slope parameters increase in their apparent effect on peak flow. Roughness parameters and channel width do not show such a trend.

A calibration method for a simple and complex drainage configuration of an optimum size 0.5 square mile unit area was developed by combining dominant slope factors into one variable and relating this variable to rainfall intensity to define equivalent cell storage constants.

The calibration method was tested with actual hydrological data available for various arid watersheds with limited success.

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CHAPTER 1

INTRODUCTION

1.1 Relevance of Study

The need for accurate and comprehensive runoff information for ungaged arid watersheds has brought about many recent developments in hydrologic modeling. The importance of obtaining such runoff response data is vast: not only in quantity assessment for comprehensive arid region water budgets, but for flood and flash flood protection. Runoff simulation has many advantages over the conventional design and maintenance of a watershed gaging network: economy, convenience, and a reasonable degree of accuracy. Most small, and many large, watersheds are ungaged and in lieu of records for interbasin comparisons, modeling offers an alternative for obtaining peak flow estimates.

Hydrologic models can be divided into two general groups: physically based models and parametric models (Overton and Meadows, 1976). The basic outward difference between the two groups is that the physical model attempts to simulate the complex physical processes that occur during the precipitation-runoff event, whereas the parametric model ignores these processes and modifies input to runoff output by means of some mathematical transfer relation (Porter and McMahon, 1971). Physically based models generally produce more accurate output due to their approximate simulation of the real system. These models, however, require large amounts of data and are expensive to operate. Parametric models are less expensive to run and generally require less input data, but their disadvantage is that there must be an initial calibration with field data or with some type of synthetic data such as data produced from a physically based model.

One of the more innovative parametric models is the quasi-linear spatially distributed cell model developed by Diskin and Simpson (1978). The attractive feature of this cell storage model is its ability to accept distributed rainfall input and route the rainfall excess through interconnected cells that mimic the major drainage network of a natural watershed. Outflow from each cell is determined by a time constant that, when allowed to vary from storm to storm and cell to cell, enables the model to be quasi-linear in response to rainfall input.

The time constant, or cell storage ratio, is not a directly measureable entity and has, in the past, been determined by trial and error calibration for a specific watershed. The cell storage ratio has been found to be related to rainfall excess and certain hydraulic properties of the watershed (Diskin and Simpson, 1978).

1.2 Objective of Study

The objective of this study is to define the cell storage constants of the quasi-linear spatially distributed cell model in terms of the most influential hydrologic characteristics of the ephemeral watershed. By initially determining the storage constant of each cell of a multi-celled watershed trial and error calibration for a particular watershed can be bypassed and the cell model would be able to estimate peak storm runoff resulting from extreme summer storm events directly in an ungaged ephemeral watershed.

Successful completion of the proposed calibration procedure requires a large range of rainfall-runoff data. Actual arid watershed data is either very limited, inadequate, or too site specific for use as a data base. The alternative data source, and the source of all calibration data used in this study, is a complex, non-linear, kinematic cascade model developed specifically for ephemeral channel flow by Amorocho and others (1973). The complex, physically based model acts as an intermediary between the actual watershed and the parametric model by supplying a complete range of synthetic calibration input-output data. Detailed descriptions of the cell storage model and the kinematic cascade model are given in Chapter 2.

The determination of the storage constant of the cell storage model, termed calibration method, will be conducted in three steps. First, a detailed sensitivity analysis of hydrologic charateristics will be conducted to determine the most influential factors that affect peak discharge for various sizes of watershed subunits. The results of this stage will be used to determine an optimum size watershed subunit, termed unit area, and the most influential parameters affecting peak runoff within that specific sized unit area. The unit area becomes a cell in the multi-celled parametric model representation of the natural watershed and is described by its unique cell storage constant. The second step involves the trial and error hydrograph curve fitting to match the cell storage constants of the parametric model to combinations of the influential hydraulic characteristics of the complex kinematic model. Third, the calibration method was verified by applying the parametric model to gaged arid and semiarid ephemeral watersheds and comparing observed and simulated runoff output to determine limitations, if any, of the model or method.

The generalized flow chart of the calibration procedure to determine values of the cell storage constants of the cell storage model is illustrated in Figure 1.1.

1.3 The Rainfall-Runoff Process in Arid Watersheds

The hydrology of arid watersheds is characterized by high intensity, limited areal extent precipitation, limited soil moisture, high evaporation, large transmission losses, and low annual surface water yield (Renard, 1970).

The intensity of rainfall may be more important than the total amount, although runoff tends to increase with the duration of the rain event. Most ephemeral channels in the southwest discharge water only when a moderately heavy rain, resulting almost exclusively from summer thunderstorms, falls on the drainage basin. The spatial variability and limited areal extent of summer thunderstorms complicate runoff patterns in a given watershed, especially if the area of the catchment is considerably larger than the area of the storm (Osborn and Hickok, 1968).

The characteristic large percentage of summer rainfall that is returned to the atmosphere is due to the seasonally high temperature and aridity. Evaporation of water from the soil is enhanced due to low plant density. Consequently, deep drainage to ground water is seldom achieved and soil moisture is generally minimal (Kincaid and others, 1964).

Because of high evaporation losses and sparse vegetation the degree of slope exercises a stronger control on the amount of runoff in arid areas than in humid

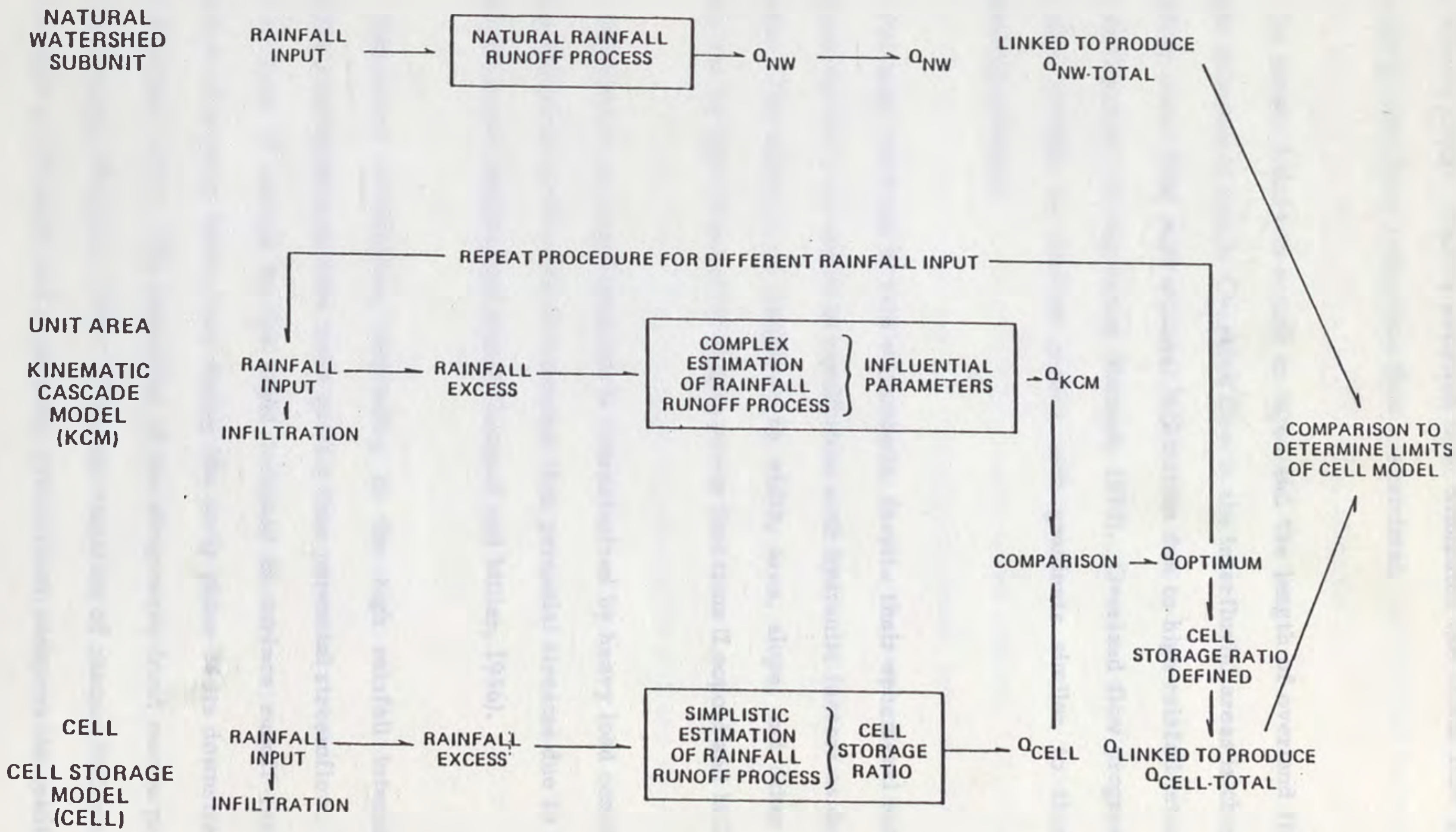


Figure 1.1. Flow chart of the calibration procedure used to determine values of the cell storage constants of the cell storage routing model.

areas (Chow, 1964). Horton overland flow dominates the storm flow hydrograph and contributions from subsurface flow are minimal.

On desert hillslopes runoff is rapid and the length of overland flow before channel entrance is small. Overland flow in the interfluvial areas is characterized by diffuse sheet flow with minimal infiltration due to high rainfall intensity, thin soils, and sparsity of vegetation (Renard, 1970). Overland flow progresses to rill flow that travels to shallow gullies with gradients similar to those of the surrounding hillslope.

Drainage channels in arid watersheds, despite their ephemeral nature, show the same tendency to adjust in equilibrium with hydraulic factors as do perennial streams. The relation of discharge to width, area, slope, and other hydraulic factors can be approximated by simple power functions (Leopold and Miller, 1956).

Streamflow in larger channels is characterized by heavy load conditions with greater increases in velocity downstream than perennial streams due to the aggradation of steeper longitudinal slopes (Leopold and Miller, 1956).

Ephemeral streamflow, responding to the high rainfall intensity storm, generally attains its peak flow more quickly than perennial streamflow. This rapid time to peak is caused by the rapid increase in surface runoff rate and the formation of a steep wave front during the early phase of its downstream movement (Peebles, 1975). The formation of the steep wave front occurs primarily by two mechanisms (Peebles, 1975). First, the variation of channel infiltration rates, from highest at the front and decreasing downstream, steepens the leading edge of the wave as it moves downstream. Second, the deeper part of the wave near the wave peak moves faster than the leading edge of the wave, which causes the wave peak to approach the wave front until the two coincide.

The surface water yield per unit area generally decreases with increasing watershed area. This phenomenon is a result of large transmission losses in the major channels of the drainage network that contain large volumes of coarse textured high porosity alluvium. Transmission losses are the primary groundwater recharge source in many limited rainfall areas (Renard, 1970; Wallace and Renard, 1967). The magnitude of transmission losses for any flow event is extremely variable, but seems to be related to flow duration, channel length and width, antecedent moisture conditions, and the volume and characteristics of the channel alluvium (Burkham, 1970).

A generalized water budget for summer seasons in arid and semiarid watersheds is illustrated in Figure 1.2 (Renard, 1970).

1.4 General Description of the Study Watersheds

The ultimate goal of the study seeks to develop a simple, non site specific method for predicting peak discharges from extreme summer storm events without model adjustment. To validate the method, seven instrumented watersheds in three western locations were modeled and comparisons drawn between observed and computed flow. The selection of watersheds was based upon the availability of short time interval storm rainfall-runoff data. This information was obtained from the Agricultural Research Service, United States Department of Agriculture (1962-1972).

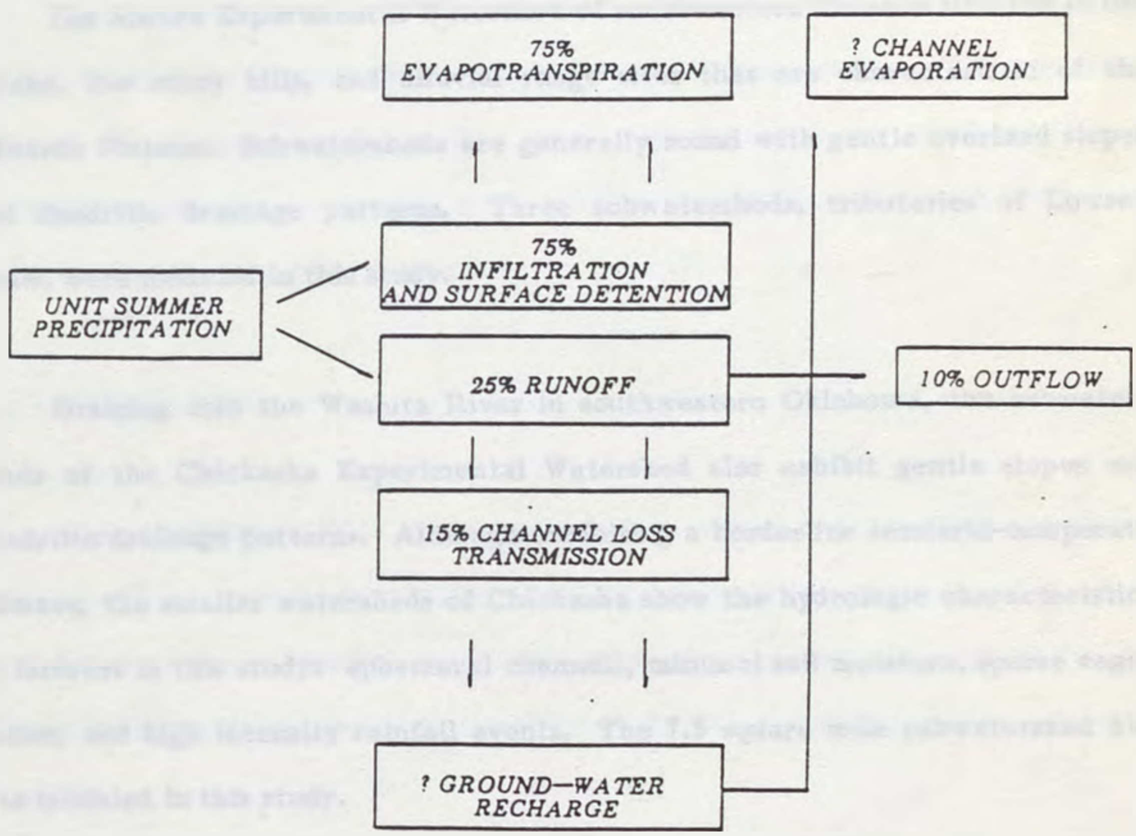


Figure 1.2. Generalized summer water budget for arid and semiarid watersheds (Adapted from Renard, 1970).

The Walnut Gulch Experimental Watershed, located in southeastern Arizona, is representative of the physiography of the Basin and Range Province. Parallel drainage patterns are common resulting in long, narrow, steeply sloped subwatersheds. Three subwatersheds, ranging in size from 3.5 square miles to 15 square miles, were modeled in this study.

The Sonora Experimental Watershed of southwestern Texas is situated in the upland, low stony hills, and alluvial range sites that are characteristic of the Edwards Plateau. Subwatersheds are generally round with gentle overland slopes and dendritic drainage patterns. Three subwatersheds, tributaries of Lowrey Draw, were modeled in this study.

Draining into the Washita River in southwestern Oklahoma, the subwatersheds of the Chickasha Experimental Watershed also exhibit gentle slopes and dendritic drainage patterns. Although exhibiting a borderline semiarid-temperate climate, the smaller watersheds of Chickasha show the hydrologic characteristics or interest in this study: ephemeral channels, minimal soil moisture, sparse vegetation, and high intensity rainfall events. The 7.5 square mile subwatershed 611 was modeled in this study.

More detailed descriptions, and generalized maps, of the watersheds tested in this study are contained in Appendix A.

CHAPTER 2

DESCRIPTION OF MODELS

2.1 The Quasi-linear, Cell Storage Routing Model

The quasi-linear, spatially distributed cell model (Diskin and Simpson, 1978) is classified as a lumped parameter, non-linear storage model. The attractive feature of lumped models is that they need a relatively small number of parameters and are, generally, more simpler less costly to operate than more complex runoff simulation models.

2.1.1 Model Theory

The quasi-linear parametric model is a series of cascading reservoirs, termed cells, that represent the branching drainage system of a watershed. Each cell has a separate rainfall input, thus allowing the model to account for the spatial distribution and temporal distribution of rainfall over the catchment during a storm.

Each sell in the model is assumed to act as a linear reservoir characterized by a storage ratio, K (Figure 2.1). The storage ratio, or cell storage constant, is defined as the ratio between the quantity of water in storage in the cell and the rate of outflow from the cell (Diskin and Simpson, 1978). The storage ratio (t) is related to output y(t) (l/t) by the storage equation:

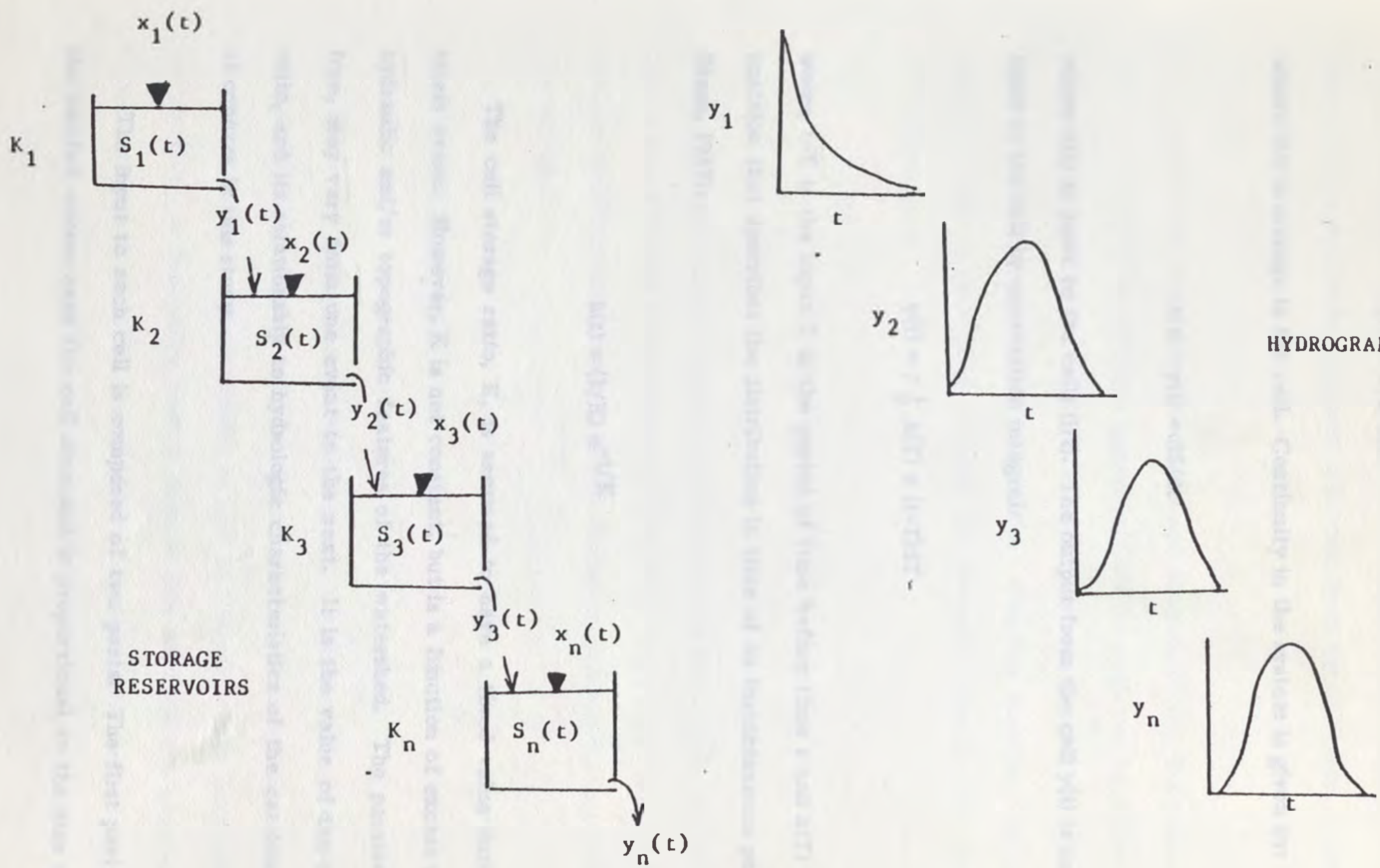


Figure 2.1. Routing instantaneous inflow through a series of linear storage reservoirs (Adapted from Nash, 1957).

$$y(t) = 1/K\ S(t) \tag{2.1}$$

where S(t) is storage in the cell. Continuity in the system is given by:

$$x(t) - y(t) = dS/dt \tag{2.2}$$

where x(t) is input to the cells (l/t). The output from the cell y(t) is related to the input to the cell by convolution integral:

$$y(t) = \int_0^t h(T)\ x\ (t-T)dT \tag{2.3}$$

where t-T is the input T is the period of time before time t and h(T) is the input function that describes the distribution in time of an instantaneous pulse of input (Nash, 1957):

$$h(t) = (1/K)\ e^{-t/K} \tag{2.4}$$

The cell storage ratio, K, is assumed to have a fixed value during any one storm event. However, K is not constant, but is a function of excess rainfall and hydraulic and/or topographic features of the watershed. The parameter, therefore, may vary from one event to the next. It is the value of the cell storage ratio, and its relationship to hydrologic characteristics of the catchment, that is of concern in this study.

The input to each cell is composed of two parts. The first part is equal to the rainfall excess over the cell area and is proportional to the size of the cell.

The second part is equal to the sum of the outputs of all interconnected upstream cells. All inputs, from upstream cells and from precipitation, combine to form one output per cell.

As initially formulated by Diskin and Simpson (1978), the parametric model has the capability to calculate excess rainfall for each cell by means of a simple percentage loss function. This routine, however, was found to be a poor representation of the actual infiltration process. The loss function was subsequently replaced with a simplified version of Horton's equation for the potential infiltration rate:

$$f(t) = f_c + (f_o - f_c)\, e^{-k(t)} \tag{2.5}$$

where f_o is the initial potential infiltration rate (l/t), f_c is the ultimate infiltration rate (l/t), and k is Horton's constant (t^{-1}). The routine is considered simple because the infiltration function is not shifted to account for any initial infiltration deficit.

2.1.2 Method of Operation

Using the drainage pattern as a guide, the watershed is subdivided into a number of cells. Each cell can be considered of equal area or assigned a percentage of the total watershed, as long as the sum of the percentages equals 100 percent. A monitoring routine ensures that all cells are processed in their correct order and combines the outputs of the upstream cells to form input to downstream cells according to the design of the model (Figure 2.2).

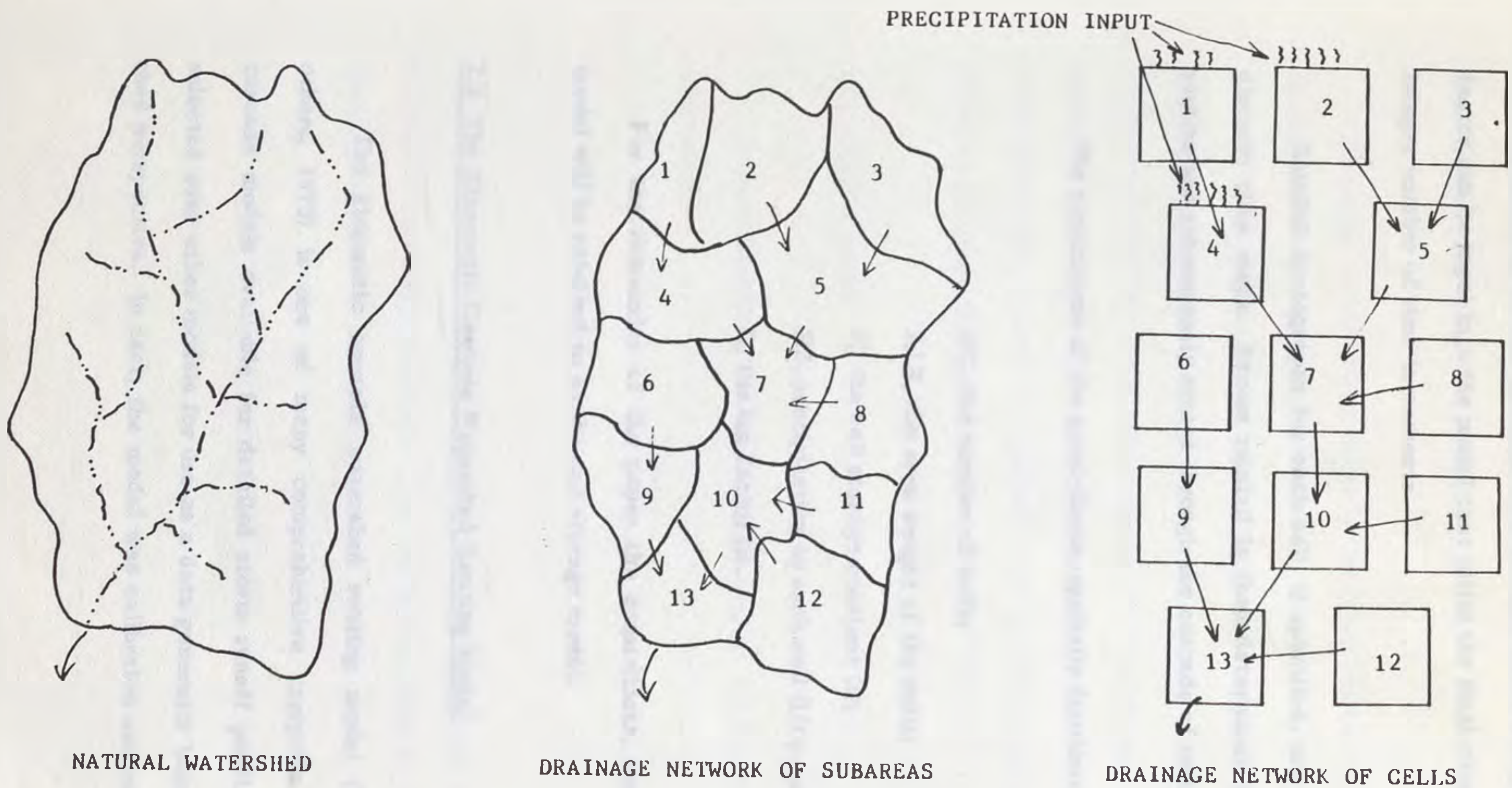


Figure 2.2. Cell drainage network, including rainfall input, for the quasi-linear, spatially distributed cell model.

In addition to the specific cell storage ratio assigned to each cell, a lag factor can be input into the model that shifts the final computed hydrograph by an integer number of time increments.

Rainfall hyetographs for each cell, if specified, are read into the model in discrete time steps. Excess rainfall is then determined by Horton's infiltration routine and subsequently routed through the cascade of cells.

The parameters of the quasi-linear, spatially distributed model are:

NC, the number of cells;

ALF, the area weight of the cells;

K, the cell storage constant (t);

RJ, precipitation to each cell (l/t); and

L, the lag factor (t).

For the remainder of the paper the quasi-linear, spatially distributed cell model will be referred to as the cell storage model.

2.2 The Kinematic Cascade Watershed Routing Model

The kinematic cascade watershed routing model (KCM) (Amorocho and others, 1973) is one of many comprehensive complex, non-linear kinematic cascade models available for detailed storm runoff prediction. The KCM was selected over other models for use as a data generator because of its arid watershed perspective. In fact, the model was calibrated and verified with hydrologic data from the Walnut Gulch Experimental Watershed, a densely gaged arid watershed located in southeastern Arizona.

Although considered complex in its computations of the physical processes involved in the rainfall-runoff process, the kinematic cascade model requires limited input information: field measured parameters that represent the geometry, roughness, and infiltration properties of the actual watershed. The simplification of the complex topography to a combination of plane and channel sections, each with their own set of hydraulic properties, interconnected with other plane and channel sets greatly reduces the computation time involved to solve the general equations of flow.

2.2.1 Model Theory

Unsteady overland flow is approximated by the steady state stage discharge relationship:

$$q = a\,(y)^b \tag{2.6}$$

where y is the depth of flow (l), q is the flow (l^2/t) past a given section (Figure 2.3), and a and b are constants. The well known form of this relationship is the Manning Equation for turbulent flow:

$$q = (1.468/n)\, S^{1/2}\, y^{5/3} \tag{2.7}$$

where n is the Manning coefficient (feet$^{1/6}$) and S is the slope of the energy grade line. At equilibrium rainfall excess inflow equals outflow:

$$q = nx = a\,(y)^{\,b}$$

where x is the distance from the upper edge of the planar element (Figure 2.3) and n is the rainfall excess (l/t).

Considering the empirical equations for detention storage (D_e) as a function of the constants a and b in equation 2.6, and approximations of flow depth (y) in terms of detention storage, the discharge at time t, for a particular excess rainfall rate n, can be evaluated by substituation into the Manning equation:

$$q(t)=(1.486/n)(D(t)/L)^{5/3}\ (1.0+.6(D(t)/D_e)^3)\ ^{5/3}S^{1/2} \qquad (2.8)$$

where D(t) is detention storage. At equilibrium, D(t) is equal to the total detention storage, D_e. D at any time t is determined by the numerical approximation of the volumetric balance equation (Amorocho and others, 1973).

The infiltration rate is estimated by Horton's equation:

$$f(t) = f_c + (f_o - f_c)\ e^{-kt}$$

The assumption is made that infiltration initially occurs at the same rate as rainfall until the rainfall rate exceeds the infiltration rate. The potential infiltration rate function is then shifted to account for the remaining unfilled void

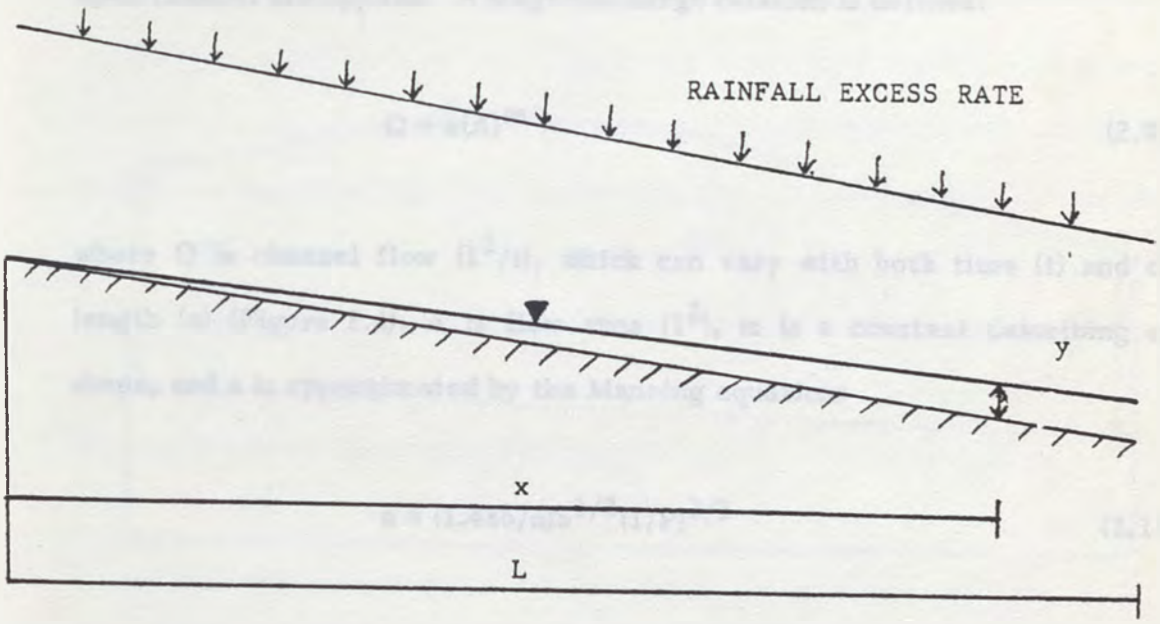


Figure 2.3. Cross-sectional sketch of a sloping planar element, receiving rain at a constant rate, showing nomenclature of overland flow equations (From Amorocho and others, 1973).

volumes in the soil resulting from the initial infiltration deficit. Additionally, any value of surface detention remaining from the previous time step is considered available for infiltration if the potential infiltration rate exceeds the rainfall rate.

Approximations to channel flow hydrographs are approached differently than the estimation of overland flow. To model the steep front wave, one that can attain considerable depth, the kinematic wave equations for unsteady flow in an open channel are applied. A stage discharge relation is defined:

$$Q = a(A)^m \tag{2.9}$$

where Q is channel flow ($1^2/t$), which can vary with both time (t) and channel length (x) (Figure 2.4), A is flow area (1^2), m is a constant describing channel shape, and a is approximated by the Manning equation:

$$a = (1.486/n)S^{1/2}(1/P)^{2/3} \tag{2.10}$$

where P is the wetted perimeter in feet. Combining the stage-discharge relation with the continuity equation:

$$\partial Q/ \partial x + \partial A/ \partial t = q_i \tag{2.11}$$

where q_i is the effective lateral inflow ($1^2/t$), the kinematic wave equation used in the model is derived (Eagleson, 1970):

$$\partial Q/ \partial t = (a)mA^{m-1} \partial A/ \partial t \tag{2.12}$$

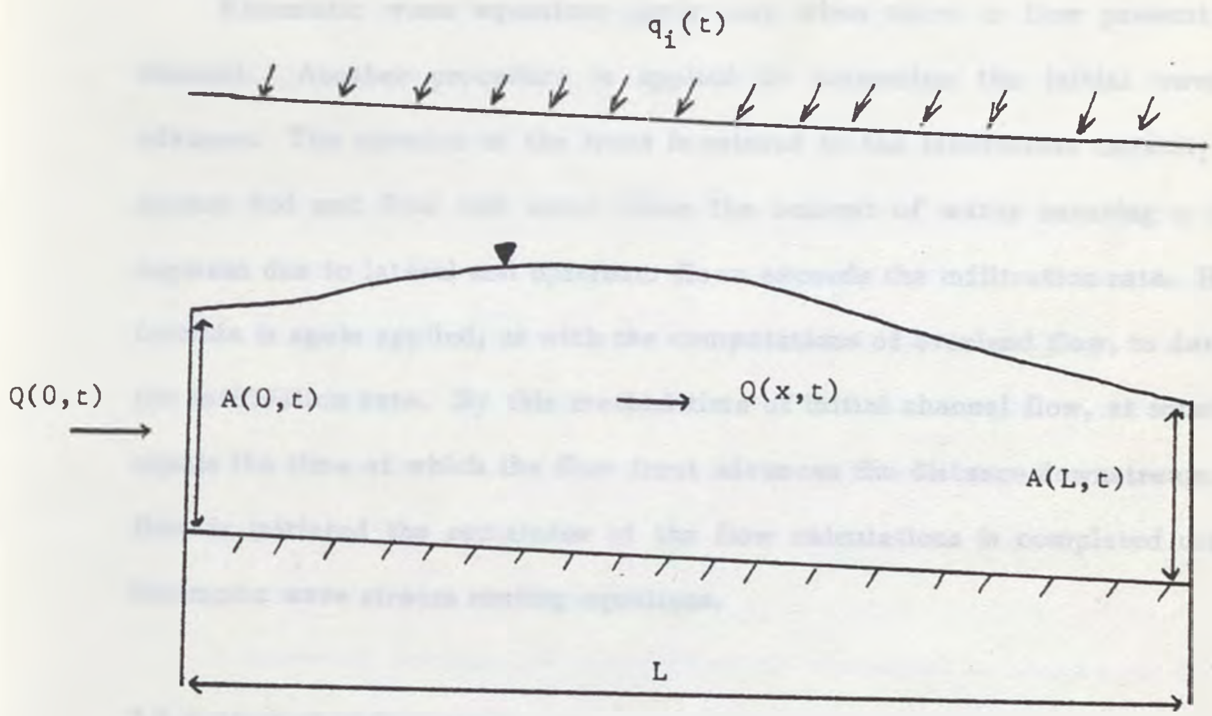


Figure 2.4. Sketch of a stream reach showing nomenclature of the kinematic wave equations (From Amorocho and others, 1973).

An explicit, finite difference solution method is used to numerically approximate the kinematic wave equation for certain solution lengths along the channel. Time is also discretized in constant steps.

Kinematic wave equations apply only when there is flow present in the channel. Another procedure is applied to determine the initial wave front advance. The advance of the front is related to the infiltration capacity of the stream bed and flow will occur when the amount of water entering a channel segment due to lateral and upstream flows exceeds the infiltration rate. Horton's formula is again applied, as with the computations of overland flow, to determine the infiltration rate. By this method time of initial channel flow, at some point, equals the time at which the flow front advances the distance downstream. Once flow is initiated the remainder of the flow calculations is completed using the kinematic wave stream routing equations.

2.2.2 Method of Operation

The watershed to be modeled is considered to consist of two principal elements: a pair of planar land elements and an intersecting stream channel element. The complex topography of the natural catchment is thus reduced to a combination of simpler planes and channel sections. By definition (Amorocho and others, 1973), the channel elements are those areas where depth of flow is large relative to its width for most flow conditions. A set of rectangular areas is delinated to approximate the shapes of laterally draining hillslopes intersecting a receiving channel. Each element requires predetermined values of descriptive geometry: width, length, and slope. These dimensions are taken off detailed topographic maps. Values of the Manning roughness coefficient and the parameters of Horton's formula are also required and must be estimated from experience or adopted from site specific field studies.

Each land element has a separate rainfall input allowing a simplified, but still distributed, representation of rainfall. Overland flow hydrographs are computed for each land segment and are routed as lateral inflow to its corresponding channel segment. The calculated hydrograph becomes the inflow to the next channel. Flow is routed in this manner, including the time synchronized addition of hydrographs from merging channels, through the drainage network by a set of coded instructions in the central program. The output at the end of the final channel is the watershed output as predicted by the kinematic cascade model.

A modeling scheme for a hypothetical watershed is illustrated in Figure 2.5. The input parameters of the kinematic cascade model are:

Land Areas:

1. Precipitation input (inches/hour)
2. Length of plane (feet)
3. Width of plane (feet)
4. Average slope
5. Manning's roughness coefficient, n (feet$^{1/6}$)
6. Initial infiltration rate, f_o (inches/hour)

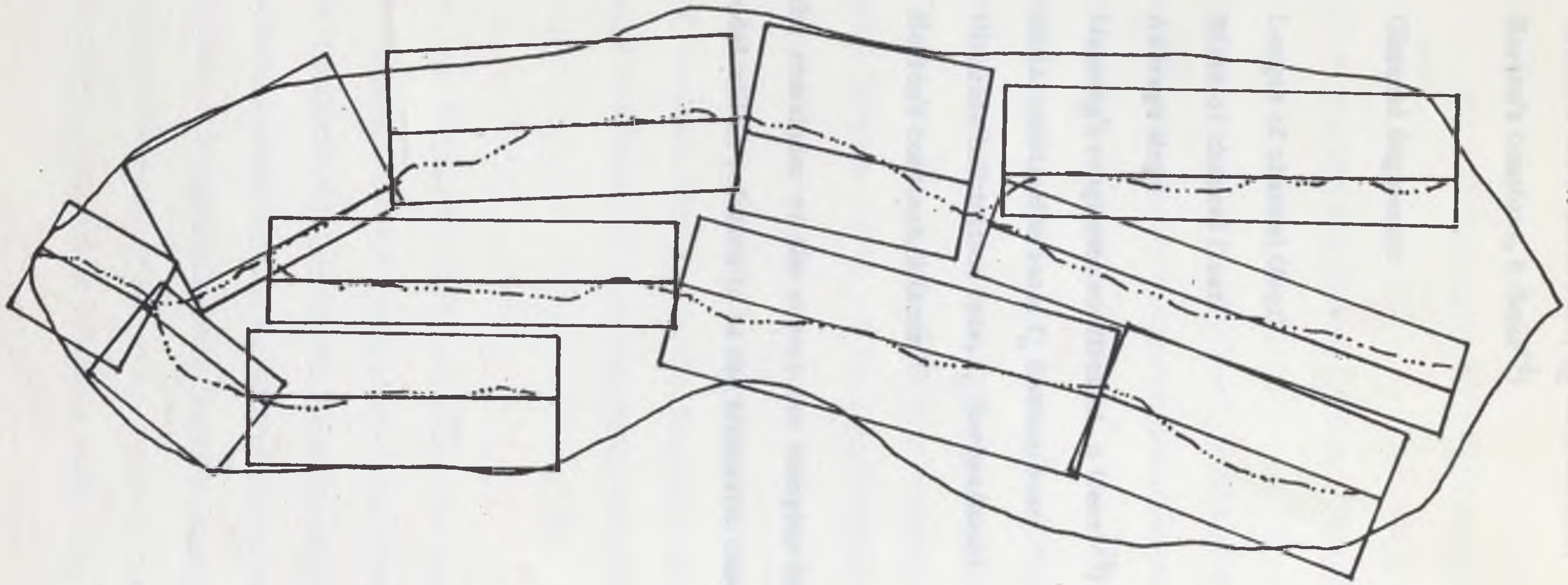


Figure 2.5. Hypothetical watershed showing subdivision into rectangular elements and straight channel segments, as required for input into the kinematic cascade model.

7. Ultmate infiltration rate, f_c (inches/hour)

8. Horton's constant, k ($hour^{-1}$)

Channel Segments:

1. Length of channel (feet)
2. Width of channel (feet)
3. Average slope
4. Manning's roughness coefficient, n ($feet^{1/6}$)
5. Initial infiltration rate, f_o (inches/hour)
6. Ultimate infiltration rate, f_c (inches/hour)
7. Horton's constant, k ($hour^{-1}$)

For the remainder of the report the complex kinematic cascade watershed routing model will be referred to as the kinematic cascade model or the KCM.

CHAPTER 3

LITERATURE REVIEW OF PREVIOUS RESEARCH

3.1 Application of Kinematic Models for Runoff Simulation

Modern research in physically based models have been based on applications of the kinematic wave theory to approximate overland and channel flow (Overton and Meadows, 1976). The properties of the kinematic wave can be described by the continuity equation and a stage-discharge relationship. The kinematic wave approximation was first used to simulate flow by Henderson and Wooding (1964). The model input steady rainfall of a finite duration and simulated flow over a sloping plane. Wooding (1965a, 1965b, 1966) adapted the kinematic equation to calculate runoff from a watershed composed of two sloping rectangular planes and an intersecting straight channel. To account for the predicted inaccuracies in the geometry of Wooding's V-shaped model Woolhiser (1969) developed a converging surface model consisting of a sloping conal surface intersected by a straight channel.

Kibler and Woolhiser (1970) accounted for variations of ground slope in terms of a kinematic cascade constructed from a series of planes of different slopes. This model was able to simplify the complex geometry of an actual watershed by replacing natural topography with combinations of similar size plane and channel sections. Comparisons made between kinematic wave and momentum solutions indicated evidence of numerical errors in this kinematic cascade model due to shock waves occurring at breaks in slope. The errors were determined to be a property of the mathematical approach rather than an observable feature of the hydraulic process. Kinematic wave equations solved by the method of characteristics have been presented that correct for the smoothing errors resulting from the numerical description of kinematic shocks (Chapman and Dunin, 1975).

Smith and Woodhiser (1971) coupled a simple infiltration routine to each plane of a kinematic cascade. Infiltration at any point on the overland slope was solved by a one dimensional, vertical saturated-unsaturated flow calculation for one or more soil layers. Overland flow with infiltration was solved simultaneously by coupling kinematic equations with the vertical infiltration equation. In addition to the simulation of continuously infiltrating planes the kinematic cascade model incorporated into its channel routing procedure a transitional friction relation that distinguishes laminar flow from turbulent flow by interpreting transitional depths of flow. This innovation, along with its complex routing procedures resulted in an improved representation of the real flow system. The model was tested against laboratory runoff experiements and small agricultural watersheds with reported reasonable agreement. The model fit with natural runoff records, however, required interim calibration of the roughness parameters and initial subsurface moisture parameters.

Chery (1976) expanded the model proposed by Smith and Woolhiser (1971) by modifying the routing procedure to incorporate more cascading planes with interconnecting channels and including the ability to input spatially distributed input and then separate it into precipitation excess and infiltration (Smith and Chery, 1973). Both innovations enabled the satisfactory simulation of peak runoff hydrographs for selected watersheds of the southwest United States.

Amorocho and others (1972) developed a kinematic cascade model specifically for ephemeral watersheds. The unique model included methods to simulate the initial wave front advance of stormflow through the ephemeral channel. The advance of the front was related to the infiltration capacity of the stream bed and the amount of water entering a given channel segment from upstream and lateral flow. A versatile routing procedure and variable catchment sizes enabled a variety of watershed shape and sizes to be modeled. Details of the model theory and method of operation are given in Chapter 2.

The Amorocho model was tested with numerous convective storms measured on subcatchments of the Walnut Gulch Experimental Watershed in Arizona and the Alamogordo Creek Watershed in New Mexico. Simulation results compared well with observed flow, especially with the peak flow and time to peak aspects of the stormflow hydrographs. Amorocho (1972) noted a larger sample of storms were necessary for complete statistical confidence in some of the parameters entering the model.

3.2 Application of Parametric Linear Storage Models for Runoff Simulation

The earliest uses of a parametric model to estimate runoff was the estimation of coefficients that were multiplied with design storm rainfall intensities to predict peak flow rates (Overton and Meadows, 1976). These coefficient relationships are linear and dependent upon watershed characteristics such as rainfall and elevation. Horton (1938) proposed a parametric model based on the division of surface runoff into three components: overland flow, channel flow, and a base flow component. The numerical solution was calculated by a linear approximation of the kinematic flow equation.

The evolution of parametric linear storage models for runoff simulation dates from the Nash model (1957) of Sherman's (1932) unit hydrograph concept. Nash (1957) developed a model that considers the routing of effective rainfall through a series of cascading equal dimension linear reservoirs, defining the instantaneous unit hydrograph for the system at a specific time as a density function related to a storage coefficient and the number of linear reservoirs. In routing the flow, the outflow from the first reservoir is the input to the second reservoir (Figure 2.1).

Improvements to Nash's concept of cascading reservoirs were made by Dooge (1959) who modified the surface runoff routing system to include a combination of linear cells and linear channels. Another adaptation of unit hydrograph flow was the routing of two cascading linear reservoirs systems in series: one to simulate overland flow and the other to simulate channel flow (Diskin, 1964).

The early achievements with linear storage models were of limited use for field studies of storm runoff because the models were generally much simpler than typical drainage processes of natural watersheds. The enhancement of more complex routing systems and distributed input capabilities enabled natural watersheds to be modeled.

Van de Ness and Hendriks (1971) developed a distributed input linear storage model in which the watershed is represented by a network of overland and channel elements that receive their input as a concentrated upstream inflow and uniformily distributed lateral inflows.

Diskin and Simpson (1978) advanced the earlier proposed concepts of linear reservoir response by developing a parametric model that accounted for mild non-linearities by allowing the reservoir storage parameters to vary with differing storms intensities. The model is conceptually similar to one developed by Campana (1975) to represent transport processes in ground water systems. The model can accept spatially and temporally distributed inputs and can be adjusted to various cell size arrangements and routing networks. A detailed description of model theory and method of operation is given in Chapter 2.

The Diskin and Simpson (1978) model was tested with rainfall excess and direct surface runoff data from a 247 square mile watershed in the eastern United States. Satisfactory matching of observed and simulated peak runoff was obtained for five storms by trial and error adjustment of a single watershed storage parameter. Increasing the number of cells, therefore decreasing the size of each individual cell, resulted in generally better hydrograph comparison after a downward adjustment of the storage parameter. Limitations of the model verification were noted to be the lack of detailed spatial distribution of rainfall for each storm.

3.3 Determination of the Storage Parameters of the Linear Storage Model

As previously discussed, the initial application of parametric linear storage model for peak flow predictions in natural watersheds required the trial and error adjustment of the cell storage parameter. This task is difficult to accomplish if rainfall-runoff data are limited or not available. The key to the successful application of parametric models to predict peak flow hydrographs in gaged and ungaged basins is the determination of storage parameters in terms of hydrologic variables. Recent efforts have been made to define the cell storage constants of parametric storage-routing models by relating them to watershed characteristics.

Buapeng and Singh (1977) applied a regression and correlation analysis to determine predictive equations for the time constants of a three cell cascading reservoir model. Independent variables included only map measurable topographic characteristics of watersheds. Poor relationships were exhibited between time elements and watershed parameters. Geographical variation of the study data and the variation in the areas of the cells within each tested watershed may have contributed to the poor correlations.

Bond (1977) developed a calibration procedure for a single predetermined subunit of a watershed. Each subunit, termed base area, was modeled as a discrete number of planes and channels. Calibration data were generated from a physically based kinematic wave model. A procedure to link base area response together to predict total watershed flow was not formulated, and no attempts were made to apply the calibration method to natural watersheds.

Boyd (1978) successfully developed a relation between lag time and drainage area and used this relationship to assign cell storage parameters to the elements of a storage-routing model based on the stream channel network. The time constant, or lag parameter, was found to be related to: stream order as a law of stream lag times, with channel magnitude as a power relation, and with basin area as a power relation. Although site specific for humid watersheds in New Zealand, similar relationships could be developed for other catchments.

3.4 Application of Kinematic Cascade Models as Data Generators

In considering the problem of prediction of catchment response to specified precipitation input in arid watersheds that are characteristically limited in such data, it is seldom sufficient to examine a few recorded responses to observed precipitation events. A full range of catchment response is necessary to accurately assess the causal mechanisms of the peak runoff hydrograph.

There are two general approaches to determining a complete sequence of input-output records: a deterministic approach based on the physics involved and probabilistic approach based on a statistical analysis of the records (Chapman and Dunin, 1975). Examples of both approaches exist (Amorocho, 1972) (Fiering, 1967). Most studies, however, are concerned with precipitation input sequences and not with the complete watershed response.

The only deterministic application of a kinematic runoff model for the generation of input-output data known to the author is the aforementioned calibration study presented by Bond (1977). The parametric model was calibrated with a physically based model developed by Chery (1976) utilizing single base areas of acre and one square mile. Generalized guidelines developed by Bond and others (1979) were adopted, with modifications, in the present study.

CHAPTER 4

SENSITIVITY ANALYSIS OF INFLUENTIAL HYDROLOGIC PARAMETERS

Many precipitation and watershed parameters affect peak runoff. These include intensity and volume of runoff, infiltration potential of the channel and catchment, antecedent moisture conditions, watershed geometry, and vegetation characteristics. It is difficult to determine the most significant parameters affecting runoff because many of these characteristics are not entirely independent.

4.1 Past Research in Determining Influential Hydrologic Parameters

Relationships between arid watershed hydrology and arid watershed geomorphology have been noted by many researchers. Osborn and others (1971b) determined rainfall-runoff regression relations for small arid watersheds (.05 to 11 acres) within the Walnut Gulch Experimental Watershed. The resulting correlation matrix indicated that variables in rainfall explained 70 to 80 percent of the variability in peak storm runoff. More importantly, watershed parameters such as slope and area did not contribute significantly to the relationship.

Statistical multiple regression techniques were used by Benson (1964) to examine the relations of peak discharge to topographic and climatic factors for a diverse range of watershed sizes in the southwestern United States. The most significant factors affecting peak flow in flash flood prone regions were found to be drainage area, rainfall intensity for a given duration, main channel slope, and basin length.

A similar study conducted on large arid basins by Murphey and others (1977) resulted in near identical conclusions. Geomorphic parameters selected for the analysis were restricted to those easily obtainable from maps and aerial photographs. Calculated regression equations implied that drainage area parameters, stream frequency, and main channel length and slope most influenced peak flow.

The conclusions of these studies are of specific interest for two reasons. First, the results aid in the formation of a more concise perspective of probable significant parameters affecting runoff in the arid and semiarid environment. Second, the studies indicate that the effects of some influential factors on peak flow vary with the size of the catchment.

4.2 Sensitivity Analysis Design

Based upon the work of previous investigators, the relative influence of certain hydrologic and geomorphologic factors was expected to vary with the size of the catchment. Therefore, a watershed subunit of fixed size and shape was sought that exhibited an optimum combination of influential runoff affecting parameters. This fixed area is defined as a unit area and corresponds to one or more combinations of planes and channel elements for the kinematic cascade model (KCM), and to one cell for the cell storage model (Figure 4.1). Each model's representation of the unit area would receive a spatially constant rainfall input hyetograph.

A sensitivity analysis was designed to determine the most influential parameters that affect peak flow for each unit area. From these results an optimum unit area was selected for calibration.

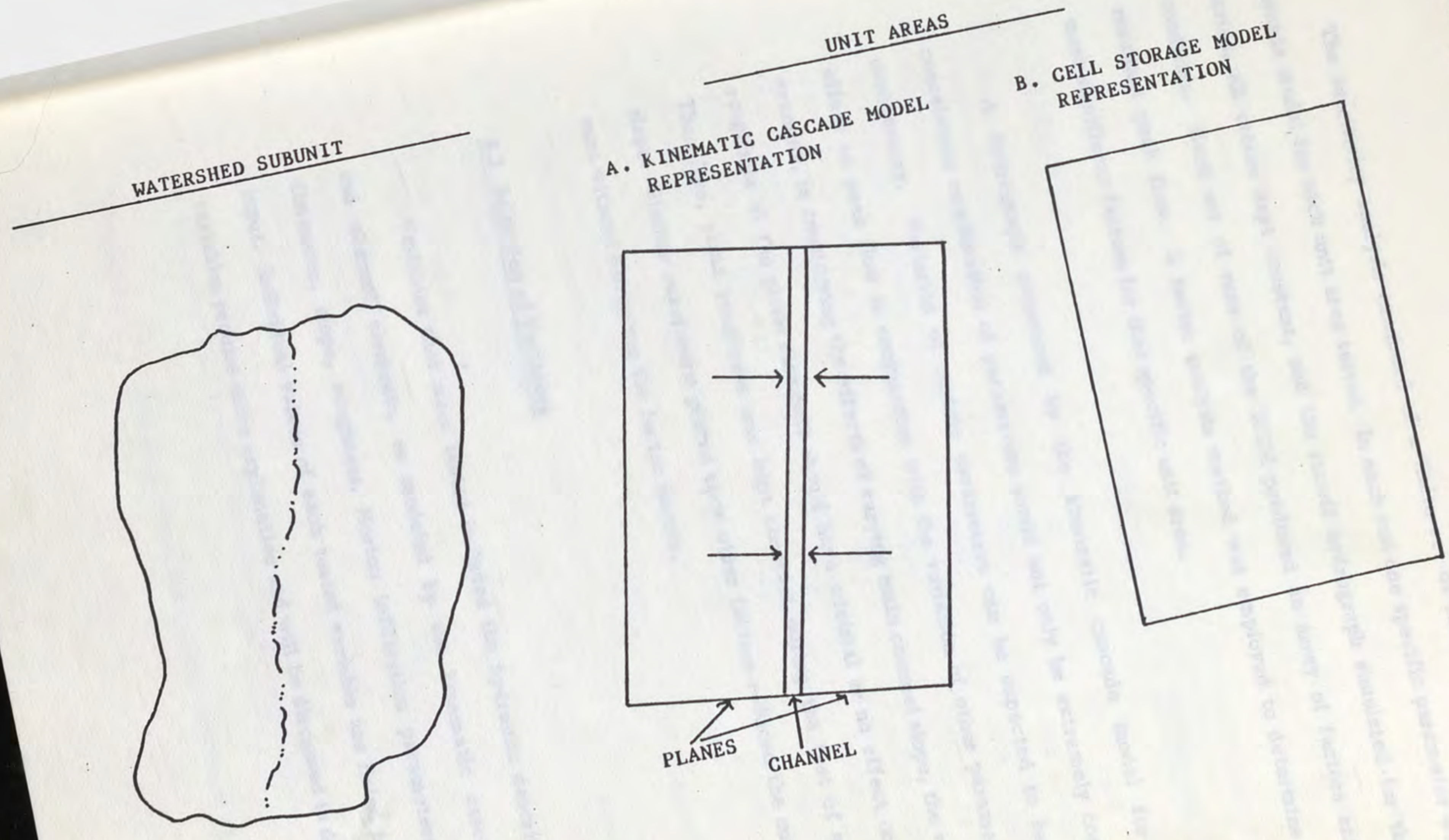


Figure 4.1. Definition of unit areas for the kinematic cascade model and for the cell storage model.

The sensitivity analysis consisted of a finite set of runs of the kinematic cascade model for each unit area tested. In each run one specific parameter was varied, all others kept constant, and the runoff hydrograph simulated for that condition. Each set of runs of the KCM produced an array of factors and a resultant peak flow. A factor analysis method was employed to determine the most significant factors for that specific unit area.

A hydrograph generated by the kinematic cascade model for every conceivable combination of parameters would not only be extremely costly, but unnecessary. Variation of certain parameters can be expected to have little effect on peak flow in conjunction with the variation of other parameters. For example, in considering the effects of varying main channel slope, the variation of roughness of the plane elements should have minimal or no effect on peak flow. Therefore, plane roughness was kept constant during the test of main channel slope. Similar constraints placed upon other factors reduced the number of KCM runs without disrupting the factor matrix.

4.3 Selection of Variables

Variables that were tested included the hydraulic description of the plane and channel elements, as modeled by the kinematic cascade model: areal dimension, slope, roughness, Horton infiltration parameters, and precipitation input. Individual values of each tested variable are listed in Table 4.1. Certain variables require more explanation and will be discussed in detail.

The range of values for each parameter was considered representative of the variety of geomorphologic characteristics expected in the arid and semiarid environment. Details on the variations of these hydraulic factors in natural watersheds are given by Leopold and Miller (1956), Barnes (1967), and Kirkby (1978).

PARAMETER	SYMBOL	TESTED VALUES		
Precipitation Intensity 30 minute duration	PI	3.0	6.0	9.0
Main Channel Slope	MCS	.005	.025	.045
Main Channel Roughness ($ft^{1/6}$)	MCR	.015	.030	.045
Main Channel Width (ft)	MCW	5	25	45
Side Channel Slope	SCS	.015	.040	.065
Side Channel Roughness ($ft^{1/6}$)	SCR	.015	.030	.045
Plane Slope	PS	.015	.065	.115
Plane Roughness ($ft^{1/6}$)	PR	.015	.030	.045
Channel Initial Potential Infiltration Rate (in/hr)	CF_o	2.5**		
Channel Ultimate Infiltration Rate (in/hr)	CF_c	0.80**		
Plane Initial Potential Infiltration Rate (in/hr)	PF_o	2.5**		
Plane Ultimate Infiltration Rate (in/hr)	PF_c	0.80**		
Peak Flow (cu. ft./sec. or in-area/hr.)	QP	Determined from each simulation.		

** Parameter held constant throughout sensitivity analysis.

Table 4.1. Ranges in hydrologic parameters tested for each unit area.

Rainfall is the primary cause of storm flow and some measure of its rate and/or volume must be closely related to the magnitude of peak flow. In arid and semiarid watersheds the outstanding characteristic of summer precipitation is its intensity and variability, both spatially and temporally. Benson (1964) noted that in correlation rainfall intensities with peak discharge, no stronger relation was found for any one duration or recurrence interval of rainfall. For simplicity, a 30 minute storm duration was selected. For example, a design storm pulse of 3 inches per hour would consist of 30 minutes of rainfall at a rate of 3 inches/hour.

The estimation of infiltration poses a problem to the design analysis of influential variables. In arid regions the variability in high intensity rainfall and the varying condition of the soil surface limit the use of infiltration values for predicting runoff without adequate sampling to characterize the variety of conditions (Hickock and Osborn, 1969). Infiltration parameters, represented in the sensitivity analysis by the variables of Hortons formula, would be expected to exhibit a large degree of influence on peak flow. Initial attempts to relate these infiltration parameters to the cell storage constants, however, were unsuccessful. Additionally, any infiltration dependent cell storage constant applied to natural systems would require soil infiltration data that may not be available in remote ungaged watersheds. For these reasons infiltration parameters were kept constant throughout the sensitivity analysis. Specific values of Hortons parameters (Table 4.1) were adoped from the kinematic cascade model calibration studies (Amorocho and others, 1973).

4.4 Selection of Unit Areas

Conceptually, hundreds of sizes and drainage configurations of watershed subunits exist that could be used as unit areas. Time and cost prevents all prospective unit areas from being tested. A set of guidelines was developed to simplify the selection procedure. First, a maximum area was sought that would still exhibit a reasonable degree of homogeneity among parameters. A large unit area has the advantage of allowing fewer cells to be processed in the application of the cell storage model to natural systems resulting in increased efficiency (less computer time) and an easier design of the cell routing procedure. Second, the size and configuration of the unit area should be such that overland flow distances from the edge of the planar element to the intersecting channel are not overestimated. Third, the unit area should be small enough to intercept a uniform rainfall hyetograph.

Based on these guidelines, six unit areas were selected for factor testing (Figures 4.2 to 4.4). For each area, the boundary that is parallel to, and on either side, of the main channel is assumed to be a relative drainage divide. The boundary perpendicular to the main channel acts as a no flow boundary for overland flow. Water transport from area to area, therefore, is assumed to occur exclusively through the main channel.

In addition to dimensional descriptions, each unit area tested is characterized by certain gross geomorphologic parameters: drainage density (D_d, miles^{-1}) and stream frequency (F_s, no./miles^2) (Strahler, 1957). In each parameter definition, unit areas was substituted for total drainage area:

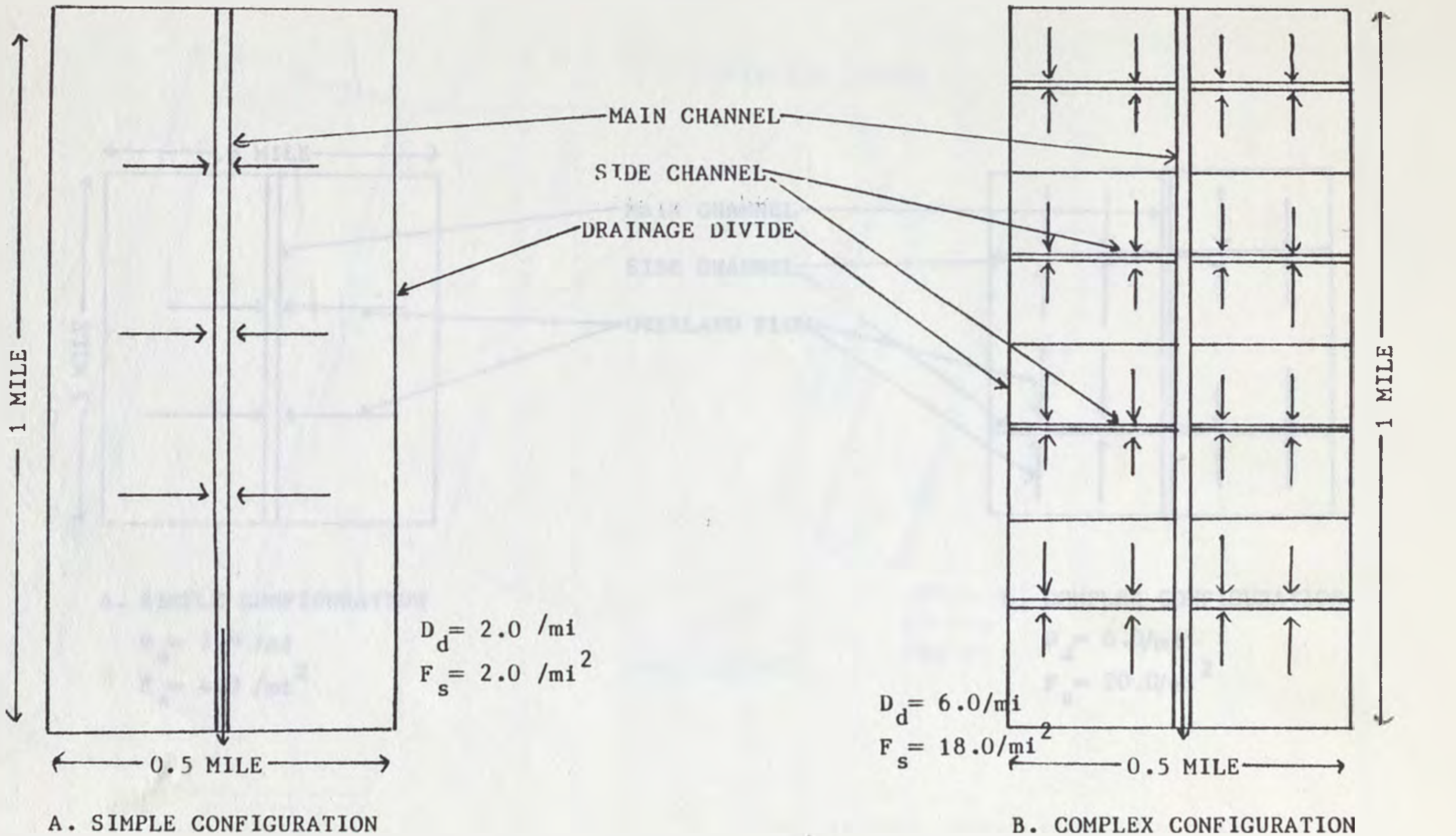


Figure 4.2. Sketch of the 0.5 square mile unit areas considered for study: 4.2a-Simple drainage configuration; 4.2b-Complex drainage configuration.

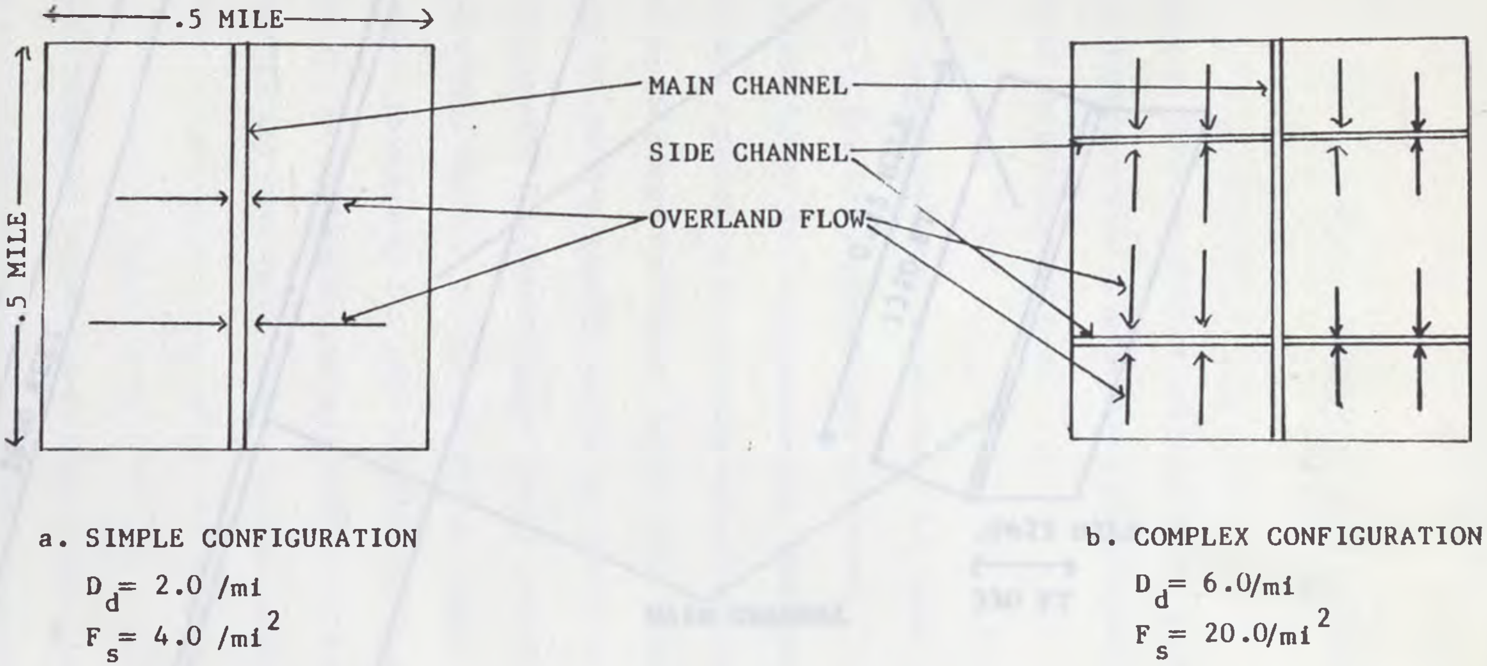
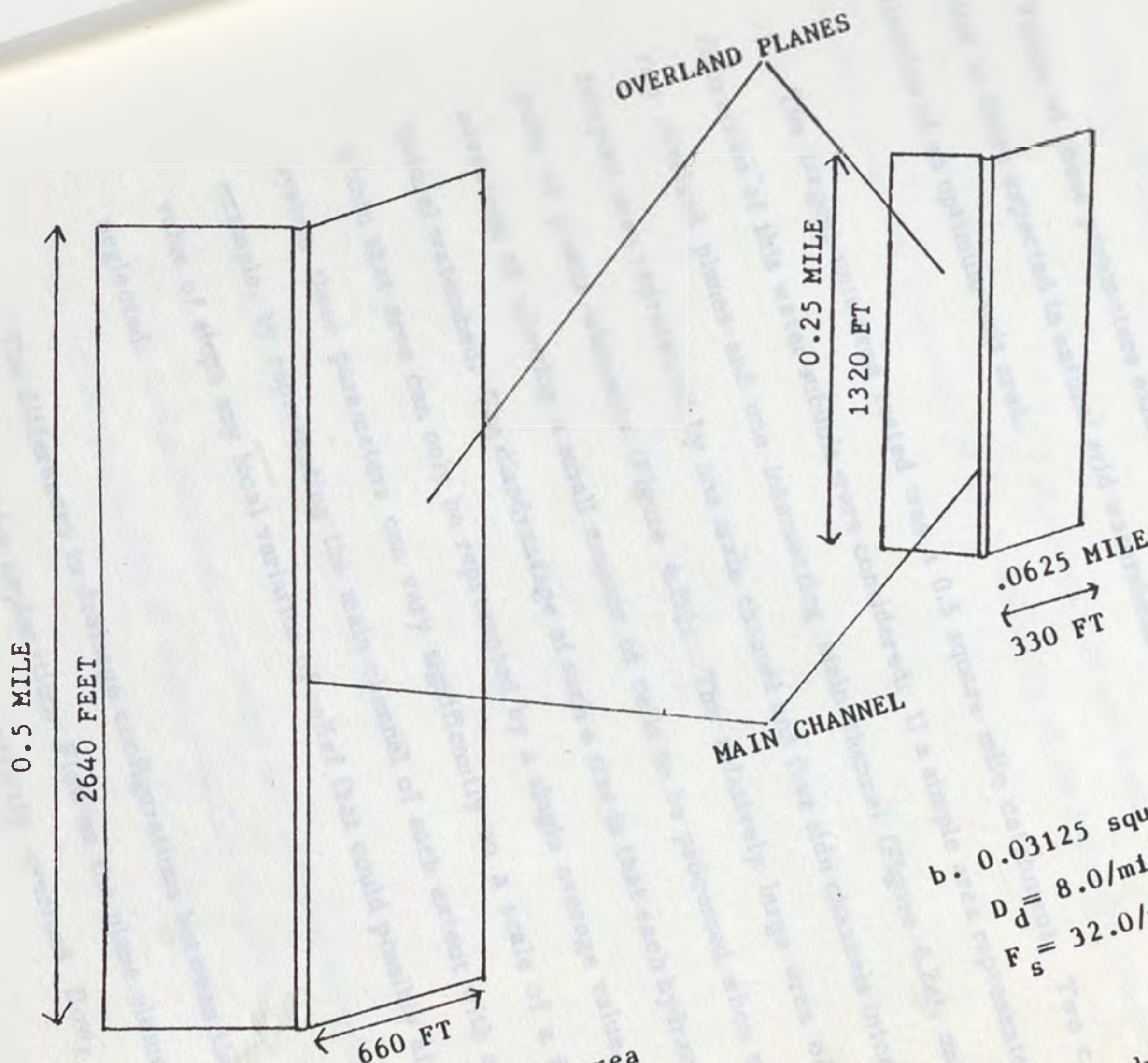


Figure 4.3. Sketch of the 0.25 square mile unit areas considered for study: 4.3a-Simple drainage configuration; 4.3b-Complex drainage configuration.



a. 0.125 square mile unit area
$D_d = 4.0/mi$
$F_s = 8.0/mi^2$

b. 0.03125 square mile unit area
$D_d = 8.0/mi$
$F_s = 32.0/mi^2$

Figure 4.4. Sketch of the smallest unit areas considered for study: 4.4a-0.125 square mile unit area; 4.4b-0.03125 square mile unit area.

$$D_d = \frac{\text{Total Length of All Channels}}{\text{Total unit area}} \tag{4.1}$$

$$F_s = \frac{\text{Total Number of Channels}}{\text{Total unit area}} \tag{4.2}$$

Values of these parameters exhibited by the prospective unit areas should be similar to those expected in natural arid watersheds and were used as an aid in the selection of an optimum unit area.

The largest unit area tested was a 0.5 square mile catchment. Two configurations of this water subunit were considered: 1) a simple area represented by two overland planes and one intersecting main channel (Figure 4.2a), and 2) a complex area represented by one main channel and four side channels intersecting pairs of planar elements (Figure 4.2b). The relatively large area offers the advantage of allowing a small amount of cells to be processed when modeling a natural watershed. The disadvantage of such a size is that each hydraulic variable within that area can only be represented by a single average value. In a natural system these parameters can vary significantly on a scale of a few feet. For example, by representing the main channel of such extent with a single average value of slope any local variation of relief that could possibly affect peak flow is neglected.

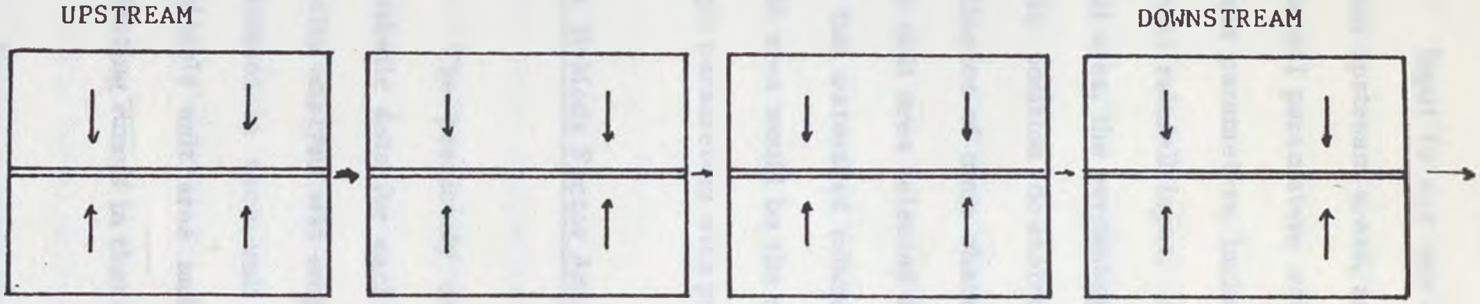
The differences in drainage configurations between the simple and complex 0.5 unit area require explanation. Flow on the plane elements of the simple area should not be considered as strictly overland flow, but as overland flow progressing downslope into rill flow. The kinematic cascade model does not have the capabilities to delineate rill flow. The complex area may also exhibit rill flow but all movement into the main channel is accomplished by the defined side channels.

A simple and complex drainage configuration of a 0.25 square mile unit area was considered (Figure 4.3a and b). The advantages and disadvantages of size and configuration between simple and complex representations, as discussed with the 0.5 square mile area, apply to the 0.25 square mile unit area. The smaller size, however, poses less constraints on the homogeneity of the hydraulic characteristics describing that area.

Two smaller areas were also selected for testing. The 0.125 square mile unit area (Figure 4.4a) and the 0.03125 square mile unit area (Figure 4.4b) were both represented by a simple drainage configuration. When considered in the natural watershed perspective both areas would be more likely to exhibit hydrologic homogeneity than the larger unit areas. A complex drainage pattern was not tested in either area.

4.5 In Series Connection of Unit Areas

Each design unit area was tested in a series of four connected equal unit areas representing a parallel drainage pattern (Figure 4.5). By testing the same combination of variables, under the same rainfall condition, any differences in the degree of influence of the hydrologic variables on runoff response between the four areas can be detected.



AREA	A	B	C	D
PERCENT TOTAL RUNOFF:				
1. FROM UPSTREAM	0%	49%	66%	74%
2. FROM WITHIN EACH UNIT AREA	100%	51%	34%	26%

Figure 4.5. An example of four unit areas connected in series. For each run of the KCM all areas have the same hydrologic parameters. Values shown are the percentages of runoff derived from upstream or in-area sources as stormflow moves from area A to area D.

Input to any one unit area can be divided into two sources: channel input from upstream areas, and precipitation input falling on that particular area. Main channel parameters would be expected to control flux from upstream cells, and plane parameters, including side channel slope, would be expected to control the direct rainfall input. As illustrated in Figure 4.5, for the same rainfall on each unit area, the percentage of total input contributed from upstream areas increases with position downstream. This trend would tend to increase the relative influence of main channel parameters at the expense of plane parameters. Since the unit area selected for calibration would be used to model the runoff response of the watershed subunit at any position in the natural watershed, the optimum unit area would be the one that exhibited minimum variance of significant hydrologic parameters with position in series.

4.6 R-Mode Factor Analysis

The previously described sensitivity analysis produced four matrices of synthetic data for each unit area tested, one matrix for each unit area in series. Factor analysis was employed to gather information on interrelationships between variables in each unit area. This information was used to select the most desirable unit area and to qualitatively identify the most influential variables affecting runoff in that specific unit area.

Factor analysis includes a number of methods that analyze interrelationships within a set of variables or objects to see whether some underlying pattern of relationships exists such that the data may be reduced to a smaller set of factors, or components. In R-mode factor analysis, the components that are created are new variables, having the form of linear combinations of the original variables. A technically lucid treatment of the many types of factor analysis, including geologic applications, is given by Davis (1973).

In this study, the R-mode principal components analysis (PA-1) offered from the Statistical Package for Social Sciences (SPSS) was employed (Nie and others, 1975). Principal components analysis determines new components in such a way that it accounts for maximum variance in all observed variables. Correlation coefficients were used as an initial measure of association between tested data. The factor model can be defined for any given data value (x_{ni}):

$$x_{ni} = \Sigma \, (f_{nj}a_{nj} + e_{ni}) \tag{4.3}$$

where f is the component score, a is the factor loading, and e is a residual, or error term. In principal component analysis the residual term is considered to be the part of the variance unexplained by factor analysis and is assumed to be small (Davis, 1973). The subscripts n and i define the dimension of the data matrix in rows and columns, respectively. The term k is the number of components to be used. Each component is orthogonal to each other and, therefore, no correlation exists between them.

The initial data matrix was scaled linearly within each particular group. This scaling enabled variables with an originally small range of values to have a similar influence in determining factor loadings as would variables with large ranges.

The R-mode principal components analysis for each unit area are listed in Tables 4.2 to 4.7. The sum of the squares of the factor loadings for each variable is the communality and reflects the proportion of the total variability accounted for by the factoring. New components are arranged in order of their importance, as indicated by their total variance. The first component is considered to be the single summary of relationships exhibited in the data as it tends to have significant loading on every variable (Nie and others, 1975). Subsequently, all decisions concerning the apparent significance of tested variables were based on the factor loadings determined for component 1. In each case the results listed for area D represent the rainfall-runoff response on area D plus the response of upstream areas A through C. Factor loadings for area B and C are not listed.

It is important to note that principal component factor analysis is not, strictly speaking, a statistical procedure. It is a series of mathematical procedures that detects patterns of influential variables. This method does not require any assumptions concerning the structure of the tested variables. For this reason, principal component factor analysis is compatible with the type of synthetic data used in this study, non random predetermined values that may not conform to a normal distribution.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.75	.78	.19	.18	-.27
MCS	.55	.69	-.24	.01	.11
MCR	.37	-.12	.12	-.49	-.31
MCW	.64	.05	.20	.73	.25
SCS	.59	.72	.06	.12	.23
SCR	.34	-.02	-.38	.09	-.44
PS	.65	.48	.57	-.30	.04
PR	.34	-.23	.32	.42	.10
QP	.83	.79	.21	.19	.35
% TOTAL VARIANCE		58.95	19.24	6.99	3.75

Table 4.2a. R-mode principal components analysis for data of Area A, complex 0.5 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.70	.77	.12	.29	-.09
MCS	.73	.71	-.21	.02	.43
MCR	.44	-.18	.61	-.10	-.15
MCW	.45	.05	.57	.01	.35
SCS	.82	.71	.08	.52	.20
SCR	.46	-.07	-.43	.09	-.50
PS	.63	.45	.61	.21	.09
PR	.38	-.19	.16	-.56	.05
QP	.82	.82	.24	.09	.29
% TOTAL VARIANCE		56.25	20.51	6.52	3.10

Table 4.2b. R-mode principal components analysis for simulated data of Area D, complex 0.5 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.83	.73	.23	.09	.49
MCS	.69	.57	.48	-.03	.37
MCR	.51	-.11	.10	.70	-.02
MCW	.45	.08	-.23	-.09	.62
PS	.75	.69	.18	.49	.02
PR	.58	-.22	-.05	.17	.71
QP	.87	.70	.49	.23	.30
% TOTAL VARIANCE		56.43	21.86	7.49	2.73

Table 4.3a. R-mode principal components analysis for simulated data of Area A, simple 0.5 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.82	.69	.21	.12	.54
MCS	.78	.61	.57	.01	.30
MCR	.60	-.18	.04	.75	-.07
MCW	.44	.11	-.07	-.14	.64
PS	.70	.67	.23	.43	.11
PR	.48	-.19	-.05	.10	.66
QP	.94	.68	.59	.07	.35
% TOTAL VARIANCE		53.52	22.43	7.37	2.04

Table 4.3b. R-mode principal components analysis for simulated data of Area D, simple 0.5 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.76	.78	.34	.18	.04
MCS	.77	.32	.77	-.10	-.26
MCR	.49	-.14	.55	.12	-.40
MCW	.40	.03	.11	-.62	.01
SCS	.66	.51	-.21	.07	.59
SCR	.30	-.09	.42	-.40	.34
PS	.97	.55	.10	.05	.81
PR	.51	-.25	.44	.33	-.40
QP	.98	.79	.44	.03	.45
% TOTAL VARIANCE		48.35	26.44	6.27	2.21

Table 4.4a. R-mode principal components analysis for simulated data of Area A, complex 0.25 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.74	.73	.42	.14	.09
MCS	.71	.36	.75	-.03	.14
MCR	.62	-.14	.63	-.02	-.45
MCW	.47	.06	.10	-.67	-.10
SCS	.72	.48	-.17	.42	.54
SCR	.49	-.11	.57	.34	.01
PS	.90	.53	.05	.17	.77
PR	.64	-.22	.45	.42	.46
QP	.92	.76	.31	.19	.46
% TOTAL VARIANCE		47.01	29.41	5.01	1.92

Table 4.4b. R-mode principal components analysis for simulated data of Area D, complex 0.25 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.85	.74	.11	.10	.53
MCS	.91	.32	-.12	.89	.01
MCR	.53	-.07	.59	-.18	-.38
MCW	.57	.03	-.75	-.08	.04
PS	.96	.58	.03	-.11	.78
PR	.77	-.13	.47	-.62	-.41
QP	.96	.78	.51	.01	.30
% TOTAL VARIANCE		49.68	28.72	8.43	5.02

Table 4.5a. R-mode principal components analysis for simulated data of Area A, simple 0.25 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.92	.71	.12	.12	.62
MCS	.76	.36	-.09	.78	.05
MCR	.48	-.11	.62	-.29	-.02
MCW	.66	.04	-.80	-.11	.09
PS	.98	.56	.36	-.19	.71
PR	.79	-.21	.30	-.65	-.48
QP	.98	.79	.49	.02	.34
% TOTAL VARIANCE		48.45	26.63	7.88	4.23

Table 4.5b. R-mode principal components analysis for simulated data of Area D, simple 0.25 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.91	.89	.24	.10	.22
MCS	.60	.15	.12	.44	-.61
MCR	.95	-.09	-.67	-.70	.07
MCW	.87	.06	.03	.85	.38
PS	.87	.22	.49	.75	.14
PR	.64	-.12	-.05	.79	-.01
QP	.96	.80	.44	.08	.35
% TOTAL VARIANCE		40.44	26.43	18.19	6.42

Table 4.6a. R-mode principal components analysis for simulated data of Area A, 0.125 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.81	.85	.20	.19	.09
MCS	.78	.18	.17	.21	-.74
MCR	.85	-.12	-.53	-.74	.10
MCW	.84	.07	.07	.85	.32
PS	.82	.21	.35	.81	.01
PR	.69	-.11	-.01	.80	-.19
QP	.97	.78	.51	.03	.31
% TOTAL VARIANCE		38.25	27.21	18.92	6.01

Table 4.6b. R-mode principal component analysis for simulated data of Area D, 0.125 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.88	.89	.10	.27	.10
MCS	.67	.17	.15	-.32	.72
MCR	.78	-.10	.83	.01	.29
MCW	.94	.03	.68	-.67	-.15
PS	.87	.19	.44	.13	.79
PR	.79	-.07	-.27	.84	-.11
QP	.92	.84	.34	.18	.25
% TOTAL VARIANCE		40.23	25.41	16.05	9.93

Table 4.7a. R-mode principal components analysis for simulated data of Area A, 0.03125 square mile unit area. Entries are factor loadings.

PARAMETER	COMMUNALITY	COMPONENTS			
		C1	C2	C3	C4
PI	.86	.87	.08	.25	.19
MCS	.75	.19	.12	-.09	.83
MCR	.77	-.11	.77	.03	.42
MCW	.93	.03	.61	-.75	-.02
PS	.95	.17	.48	.40	.73
PR	.80	-.03	-.35	.82	-.04
QP	.98	.84	.30	.33	.27
% TOTAL VARIANCE		40.78	23.11	15.48	8.70

Table 4.7b. R-mode principal component analysis for simulated data of Area D, 0.03125 square mile unit area. Entries are factor loadings.

In this study the factor loadings are interpreted as qualitative indicators of the most influential factors affecting peak flow. Variables with large factor loadings can be inferred to have significant influence on peak flow, which, in all cases, also exhibits a large factor loading on component 1.

4.7 Interpretation of Factor Analysis

Factor loadings for area A and area D of each unit area tested in series are listed in Tables 4.2 to 4.7. Three general trends are immediately evident. First, rainfall intensity appeared to be the most influential parameter affecting peak flow. This observation is supported by previously discussed field studies (Murphey and others, 1977; Benson, 1964). Second, main channel width is apparently of minimal significance on peak flow in all unit areas tested. Variations in channel width and, therefore, variations in potential magnitude of the wetted surface can significantly affect potential channel losses. Perhaps if channel infiltration parameters had been allowed to vary channel width may have exhibited more influence on the rainfall-runoff relation. This aspect of the sensitivity analysis was not pursued. Third, plane roughness and side channel roughness generally appear, with minor exceptions, to exert minimal influence on peak flow. Increased roughness, both on overland slopes and in the channels, tends to increase infiltration volume and, subsequently, decrease flow volume and peak runoff. Again, if infiltration parameters had been allowed to vary, plane roughness and side channel roughness may have exhibited more influence on the rainfall-runoff process.

The remaining factors in the sensitivity analysis vary in their influence on peak flow depending on the size and drainage complexity of the unit area.

4.7.1 Variation of Influential Factors with Size of Unit Area

The best combination of influential variables sought in this study was rainfall intensity, the most dominant parameter, plus some combination of at least two hydraulic parameters. The relative influence of hydraulic parameters on the rainfall-runoff relation is indicated by high individual factor loadings on component 1 (Tables 4.2 and 4.7). The following discussion is based upon factor loadings for area A of each unit area tested.

The 0.125 square mile unit area and the 0.03125 unit area exhibit similar factor loadings. Rainfall intensity is the principal factor in each area, with the remaining hydraulic factors exhibiting minimal influence. Plane slope does exhibit some influence, especially in the 0.125 square mile unit area, but its specific factor loading was judged too low for consideration. Of more importance, component 1 accounted for only a small percent of the total variance of the rainfall-runoff relation. Although smaller areas are more likely to possess homogeneity of parameters in the natural watershed, the low percent total variance of component 1, and the single dominant factor (rainfall intensity), eliminated the 0.125 square mile and the 0.0325 square mile areas from further consideration as the optimum unit area.

Hydraulic factors begin to show some influence on the rainfall-runoff relation as the tested unit area was increased to 0.25 square miles. Component 1 accounts for a larger percentage of total variance in both the simple and complex drainage configurations. Plane slope is the principal hydraulic factor in the simple area. Side channel slope is the principal one in the complex area.

Main channel slope exhibits increased significance in the factor loadings for both the simple drainage configurations and the complex drainage configurations of the 0.5 square mile unit area. The increased factor loading magnitude is apparently due to the increased channel length and its representation by one single slope value. The contribution of main channel slope to the relation is important, increasing the total percent variance of component 1 to 58.95%. In the complex area side channel slope was the principal factor, followed by main channel slope. Plane slope exerted some influence. Plane slope was the principal factor in the simple area, followed by main channel slope.

Based on the determined factor analysis, the 0.5 square mile unit area was judged to be the best unit area for further study for two reasons. First, for both drainage configurations, component 1 exhibited the highest total percent variance, indicating the best relation of hydrologic parameters describing the rainfall-peak runoff process. Second, for both configurations, two specific hydraulic parameters showed individual significance in their factor loadings on component 1. All other units tested had only one individual factor exhibiting significant influence.

4.7.2 Variation of Influential Factors with Complexity of Drainage Configuration

Calculated factor loadings indicated that plane parameters were the most dominant hydraulic parameters. Depending upon the complexity of the drainage network, side channel slope or plane slope was the most dominant factor.

For both the 0.5 square mile and 0.25 square mile unit areas, the complex drainage configuration better explained the simulated rainfall-peak runoff relation than the simple drainage configuration. This may be due to the ability of the side channels of the complex area to move more water rapidly into the main channel than the planar elements of the simple area. The simple drainage configuration of the larger tested areas may underestimate the movement of storm flow due to the relatively larger extents of overland flow area acted upon by set infiltration rates. This observation is supported by the differences in drainage density and stream frequency between the simple and complex drainage configurations.

4.7.3 Variation of Influential Factors with Position in Series

Expected variations in factor loadings between area A and area D (Figure 4.5) were actually very minimal. This trend indicated that principal factors, plane or channel, did not vary in their influence on peak flow as the design flood flow moved downstream. These variations were expected because of the relative changes in sources of storm water, from within the area or from upstream, as cell position shifted downstream. The observed trend indicated that a unit area could be used to model flood flow at any position in the natural watershed.

Some variation of factor loadings with position occurred in the simple drainage configurations of the larger unit areas. This variation was probably due to the relatively larger extent of overland flow areas relative to channel lengths. For this reason, the small unit areas exhibited minimum variation of factor loadings with position in series.

4.7.4 Summary of Sensitivity Analysis Interpretation

Size of the unit area, as well as the complexity of the drainage configuration, affected the relative influence of hydrologic factors on peak flow.

The 0.5 square mile unit area was chosen for use in the calibration method because of its best factor explanation of the rainfall-peak runoff relation and the strong influence of precipitation intensity and plane and channel parameters on the relation. Both tested complexities of drainage configurations exhibited these characteristics.

It was decided that both drainage configurations would be calibrated, despite the observation that the simple area may not contain the best means of slope drainage needed to accurately simulate the natural storm flow process. Not all subareas of the natural watershed contain such a strong means of slope drainage as the complex area. The two drainage configurations were considered to be the best representation of the range of complexities found in natural drainage systems.

It is not known if larger tested areas would show stronger influence of hydrologic parameters on peak flow response, as may be interpreted by the trends of the sensitivity analysis. The 0.5 square mile unit area was considered the largest area that could allow its hydraulic parameters to be represented by single average values. The observation that main channel slope exhibits increased significance with increased length is advantageous to the goals of the study, but may be problematic when trying to describe a channel of variable slope with as single slope value.

4.8 Other Factors That Influence Peak Flow

Thus far, the importance of the hydraulic characteristics of the planes and channels of the unit area have been emphasized. There are other factors that can be of some importance, such as channel storage, vegetation, and antecedent moisture conditions. The difficulties in quantifying these factors, as well as the complexities in approximating these factors in the flow equations, prevents their inclusion in the kinematic cascade model. Although these parameters were not included in the study they can potentially influence storm hydrographs and, therefore, will be discussed qualitatively.

The storage in the channel system may be a significant factor influencing peak discharge. Unusually large channels, or flood plains if present, will cause increased channel storage of storm flow and a greater potential reduction in peak discharge.

Channel vegetation, including trailing bank vegetation, can appreciably increase resistance to flow in natural channels. The effects of vegetation is most noted in the rising and falling stages of the flood hydrograph, especially in lower flow regimes (Simmons and Richardson, 1962). During peak flow stage, vegetative effects are minimal since the vegetation may be forced down, or uprooted, by the rapid movement of the water-sediment complex.

Little is known about the vegetative effects to overland flow resistance on planes. Field observations on the Walnut Gulch Experimental Watershed (Kincaid and others, 1964) indicated that increases in the percent crown spread of shrubs and half shrubs generally increase infiltration rates, resulting in smaller than predicted flow volumes and peak flows.

Runoff occurs from many storms that would not be expected to produce flow and the explanation may lie with the occurrence of antecedent moisture. Chery (1972) statistically determined that antecedent moisture conditions, present from previous rain events, significantly increased the runoff produced from convective storms affecting small watersheds (40 acres) in New Mexico. Similar results were obtained by Osborn and others (1971), but only on a low percentage of small area watersheds in southeastern Arizona. For larger watersheds, the variability of rainfall and soil characteristics often mask the affects of antecedent moisture on peak flow response.

The effects of soils and geologic characteristics are known to be highly important throughout arid and semiarid regions. Soils generally reflect the strong influence of parent rock and the minor influence of temperature and moisture.

Soils can be described by their infiltration characteristics and can be assigned numbers to represent their relative influence as directed runoff producers. In this sense direct estimates of infiltration rates, such as Hortons infiltration parameters, can be considered instead of a hydrologic soil index.

The relationship between the geology and the channel regime is important as the channel regime directly controls the channel cross-section and, therefore, the magnitude of the wetted perimeter. Channel geology, therefore, is highly correlated with potential channel transmission losses and their effects on runoff hydrographs.

CHAPTER 5

CELL STORAGE MODEL CALIBRATION METHOD

The calibration method seeks to define the storage constants of the cell storage model by establishing a relationship between the storage constant and some combination of influential runoff producing parameters. The most influential factors of the kinematic cascade model affectng peak flow, for a given unit area, were determined by the sensitivity analysis described in Chapter 4.

5.1 Calibration Method Design

The calibration procedure involved two steps. First, various combinations of dominant variables were found that generated similar output response hydrographs. The kinematic cascade model was run to simulate peak flow response from precipitation intensity input and various combinations of these dominant variables. Second, the cell storage model was pulsed, its storage constants adjusted by trial and error, until the best fit between hydrographs generated by the two model was obtained. Thus, the cell storage constant of a given cell area can be defined in terms of dominant hydrologic variables. Smooth curve extrapolation was then performed to determine a more complete range of storage constant-KCM parameter relationships without the costly generation of KCM hydrographs.

As discussed in Chapter 4, the simple and complex drainage configurations of the 0.5 square mile unit area were selected for calibration. The dominant variables of the simple unit area were determined to be precipitation intensity, plane slope, and main channel slope. For the complex unit area, dominant variables were determined to be precipitation intensity, plane slope, and main channel slope. For the complex unit area, dominant variables were determined to be precipitation intensity, main channel slope, side channel slope, and possibly, plane slope. For the remainder of the report, the simple and complex drainage configurations of the 0.5 square mile unit area will be called the simple unit area and complex unit area, respectively.

The parameters of the kinematic cascade model that exhibited minimal influence on peak flow were kept constant throughout the calibration procedure. Each factor was assigned a value that represented an average expected description of that parameter in the natural arid watershed:

Main channel roughness ($ft^{1/6}$): .030

Side channel roughness ($ft^{1/6}$): .030

Plane roughness ($ft^{1/6}$): .030

Main channel width (ft.): 25

Side channel width (ft.): 5

Channel initial potential infiltration rate (in/hr): 2.5

Channel ultimate infiltration rate (in/hr): 0.80

Plane initial potential infiltration rate (in/hr): 2.0

Plane ultimate infiltration rate (in/hr): 0.80

Horton's infiltration constant (hr^{-1}): 2.7

As noted in Chapter 2, the cell storage model has other parameters in addition to the primary fitting parameter, the cell storage constant. These parameters may have some effect on the output response of the cell storage model and, therefore, were of some concern. The area weight of the cells is constant because each cell encompasses the same area, 0.5 square miles. The lag term is capable of shifting the final computed hydrograph in time to obtain better time to peak estimations for hydrograph simulations in larger watersheds. Since good time to peak comparisons were obtained between KCM generated hydrographs and storage model computed hydrographs for the small design calibration watershed, the lag term was not studied. The same values of Hortons infiltration parameters that were input into the kinematic cascade model were also input into the cell storage model to determine precipitation excess.

As similarly applied in the sensitivity analysis, the calibration method involved the interconnection of four 0.5 square mile unit area in series. Each model, therefore, contained its unique representation of four unit areas connected in series: four plane and channel combination areas, either simple or complex, for the kinematic cascade model, and four cells for the cell storage model. For each KCM run all areas had the same parameters. Similarly, for each corresponding run of the cell storage model, each cell had the same storage constant. Storage constants were adjusted, and then statistically compared to the KCM generated hydrograph, until the best fit was obtained between the two hydrographs. All comparisons were made between output hydrographs of the final area (area D) connected in series.

5.2 Comparison Statistics and the Objective Function

The calibration procedure requires the comparison of two sets of runoff hydrographs: the generated output hydrograph of kinematic cascade model and the computed hydrograph of the cell storage model. The quantitative comparison of these curves entailed the selection of pertinent statistical measures to express the degree of agreement between computed and observed outputs. A discussion of statistical methods relevant to parameter optimization is given by Johnston and Pilgrim (1976).

In selecting the most useful statistical measures the intended objective of comparison must be considered. The overall intent of this study is to model peak flow response, while striving to preserve an overall good fit between the hydrographs. Time to peak, although of general interest, was not considered in the comparison. The three selected statistical parameters included the normalized difference between the magnitude of peaks of the two hydrographs (S_1), the normalized maximum differences between computed and observed curves (S_2), and the normalized mean absolute deviation between computed and observed hydrographs (S_3):

$$S_1 = (q_{gp} - q_{cp}) / q_{gp} \tag{5.1}$$

$$S_2 = MAX \quad (ABS\,(q_g - q_c)) \quad / \; q_{gp} \tag{5.2}$$

$$S_3 = \quad q_g - q_c \; / \; q_g \tag{5.3}$$

where:

q_g is the KCM generated flow at a given time;

q_c is the CELL computed flow at a given time;

q_{gp} is the KCM generated peak flow;

q_{cp} is the CELL computed flow; and

N is the number of data points.

A specific combination of the individual statistical measures, termed an objective function, gives a single measure of agreement between runoff hydrographs. The objective function can be weighted to reflect the more relative importance of one or more statistical parameters. In this study, since peak flow is of primary concern, greater weight was placed on the magnitude of the peaks (S_1). The objective function was defined:

$$F_s = (1/5)\ (3S_1 + S_2 + S_3) \tag{5.4}$$

An example of the variation of the defined objective function with adjustment of the cell storage constant is given in Figure 5.1. The minimum point of each curve represents the optimum cell storage constant for the given unit area, rainfall input, and influential watershed characteristics. The minimum value of the objective function identifies the best fit between the KCM generated hydrograph and the cell storage model computed hydrograph.

5.3 Simple Unit Area: Interaction Between Plane Slope and Main Channel Slope

The most dominant tested geomorphologic parameters affecting peak flow within the simple unit area were main channel slope (MCS) and plane slope (PS).

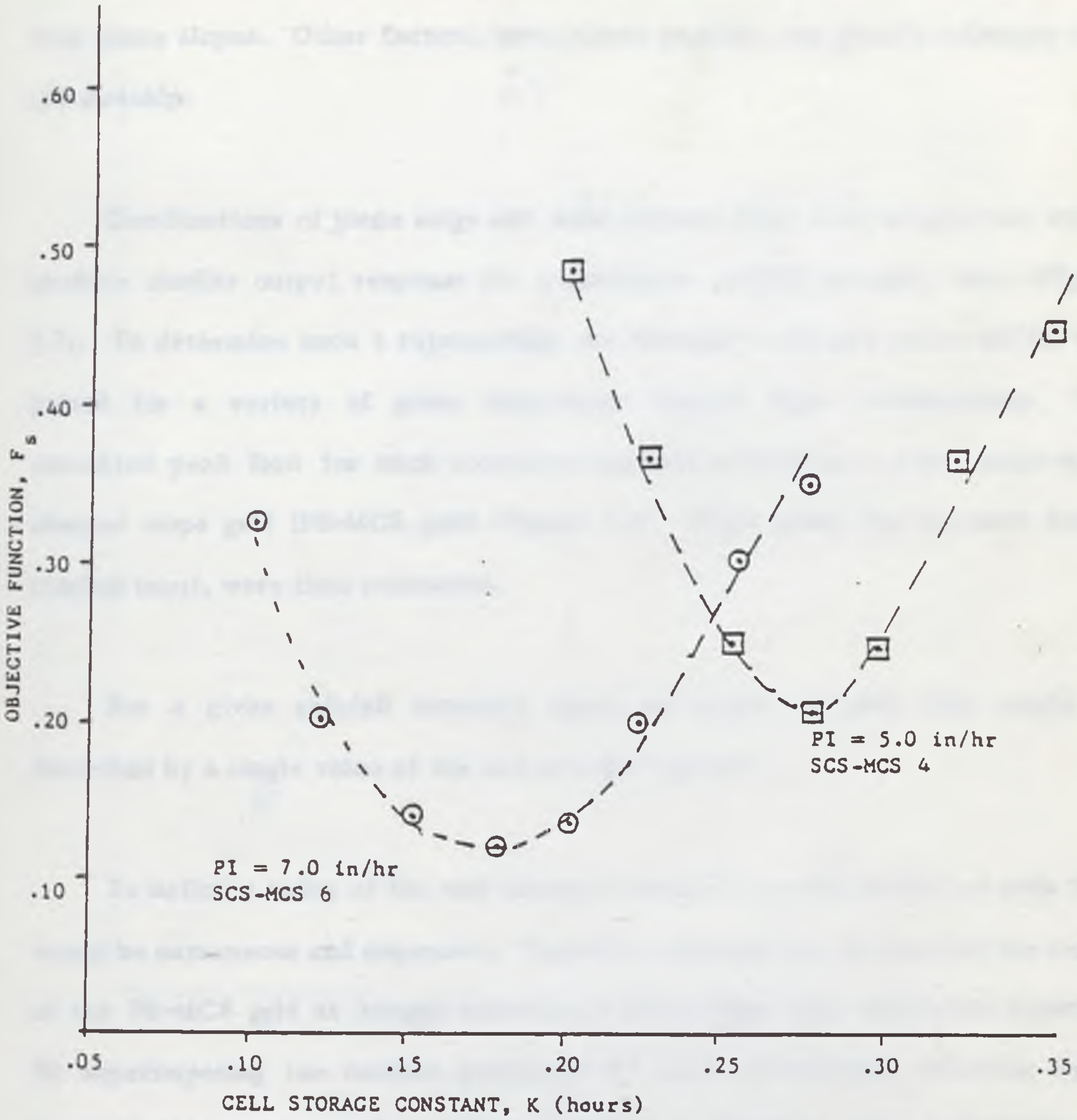


Figure 5.1. Variation of the objective function with the cell storage constant, for the complex unit area calibration method.

An interaction between the two is apparent in the natural watershed. The relationship between plane slope and channel slope in the arid setting is generally linear, as noted by Benson (1964), and Murphey and others (1977). Channels generally intersect steeper overland slopes and channel slopes are seldom larger than plane slopes. Other factors, particularly geology, can greatly influence this relationship.

Combinations of plane slope and main channel slope were sought that would produce similar output response for a particular rainfall intensity input (Figure 5.2). To determine such a relationship, the kinematic cascade model (KCM) was pulsed for a variety of plane slope-main channel slope combinations. The simulated peak flow for each computer run was plotted on a plane slope-main channel slope grid (PS-MCS grid) (Figure 5.3). These plots, one for each design rainfall input, were then contoured.

For a given rainfall intensity input, an isoline of peak flow would be described by a single value of the cell storage constant.

To define a value of the cell storage constant for every isoline of peak flow would be extraneous and expensive. Therefore, isolines that intersected the x-axis of the PS-MCS grid at integer numbers of plane slope were arbitrarily selected. By superimposing the isolines generated for each precipitation intensity input, generalized curves were drawn that represent the PS-MCS isoline distribution for all tested precipitation intensities. Each PS-MCS isoline, or isoflow, was numbered by the plane slope value that it intersected. For example, a PS-MCS isoflow that intersected the plane slope axis at .08 was labeled PS-MCS 8. The set

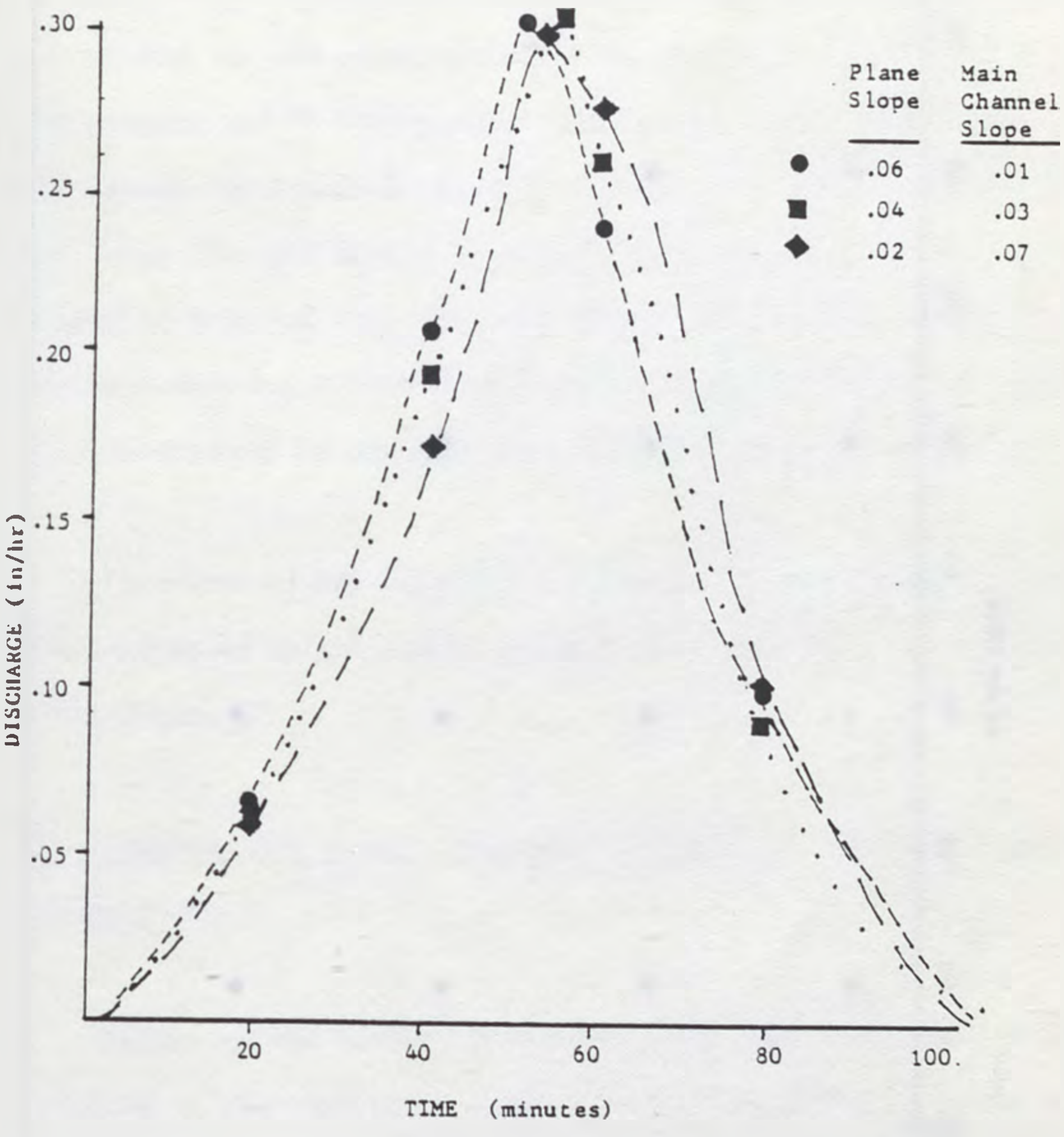


Figure 5.2. Output responses of the kinematic cascade model for the simple unit area, with a rainfall input of 6 inches per hour and various combinations of plane slope and main channel slope.

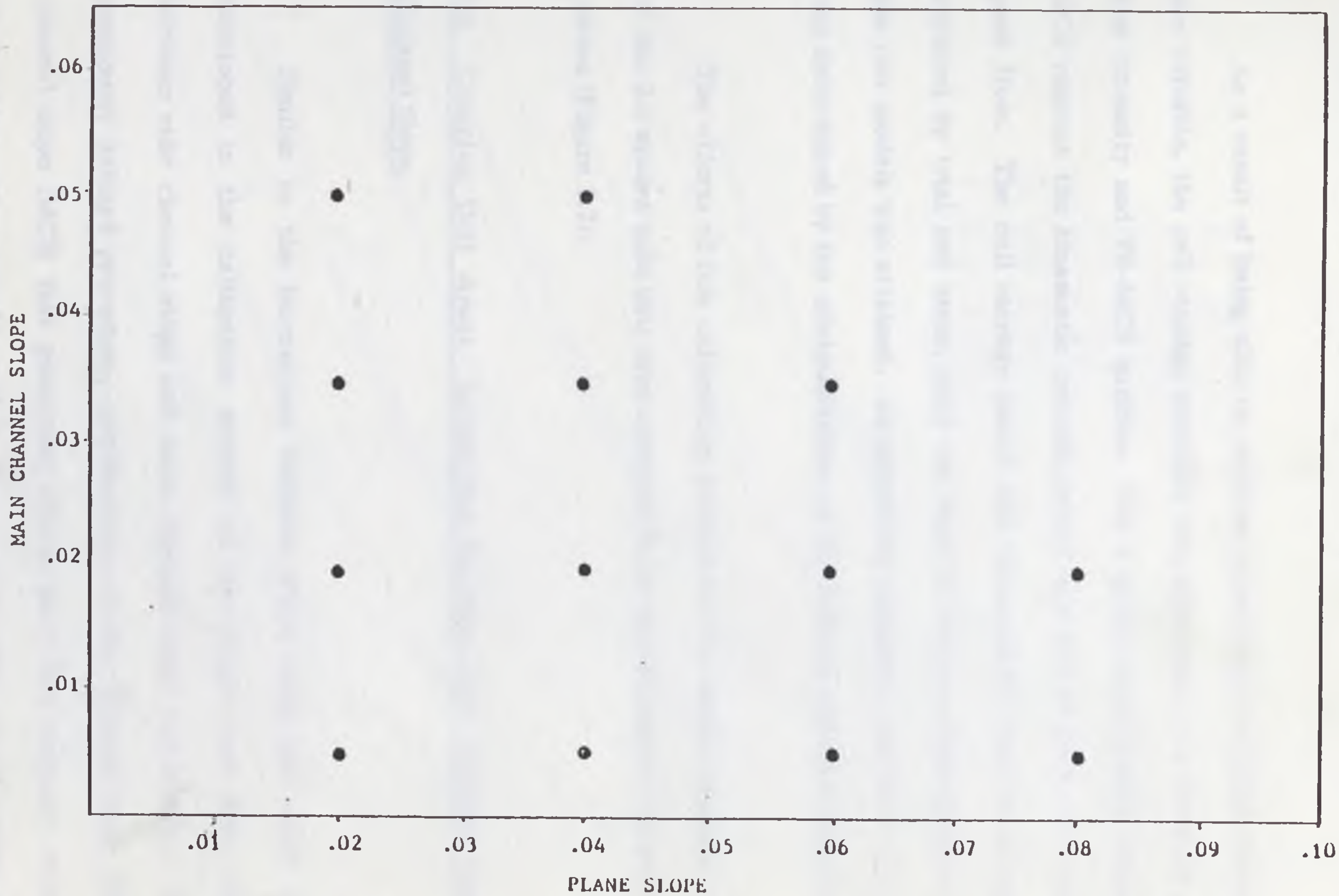


Figure 5.3. Plane Slope–Main Channel Slope (PS-MCS) grid showing combinations of plane slope and main channel slope for which hydrographs were simulated by the kinematic cascade model.

of isoflow curves and determined isolines of peak flow are illustrated in Figures 5.4 to 5.6 for precipitation intensities of 3 inches/hour, 6 inches/hour, and 8 inches/hour, respectively.

As a result of being able to combine plane slope and main channel slope into one variable, the cell storage constant was expressed as a function of precipitation intensity and PS-MCS number. For a given precipitation intensity and PS-MCS number the kinematic cascade model was run to produce a hydrograph and peak flow. The cell storage model was subsequently run, its storage constants adjusted by trial and error, until the best fit between hydrographs generated by the two models was attained. As previously discussed, the best fit of hydrographs was determined by the minimalization of the defined objective function.

The efforts of this calibration method for the simple drainage configuration of the 0.5 square mile unit area resulted in the development of a set of calibration curves (Figure 5.7).

5.4 Complex Unit Area: Interaction Between Side Channel Slope and Main Channel Slope

Similar to the interaction between plane slope and main channel slope developed in the calibration method of the simple unit area, an interaction between side channel slope and main channel slope was sought. Following the previously defined procedure, combinations of side channel slope (SCS) and main channel slope (MCS) that generated similar peak flow response were determined by the kinematic cascade model. The resulting side channel slope-main channel

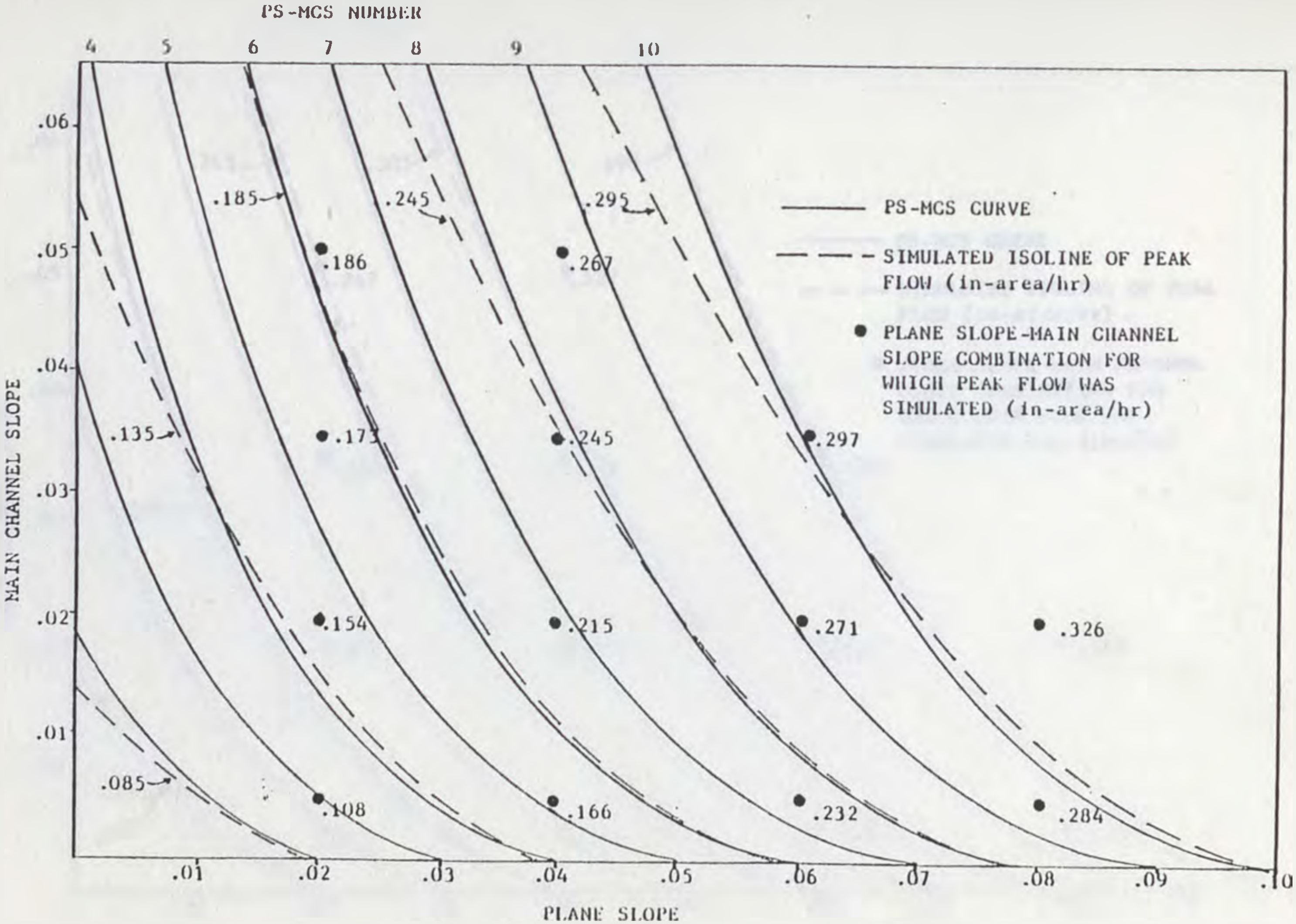


Figure 5.4. Set of PS-MCS curves and simulated isolines of peak flow for the simple unit area receiving a 3 in/hr design rainfall intensity input. Peak flow isolines are shown for PS-MCS numbers 2, 4, 6, 8, and 10.

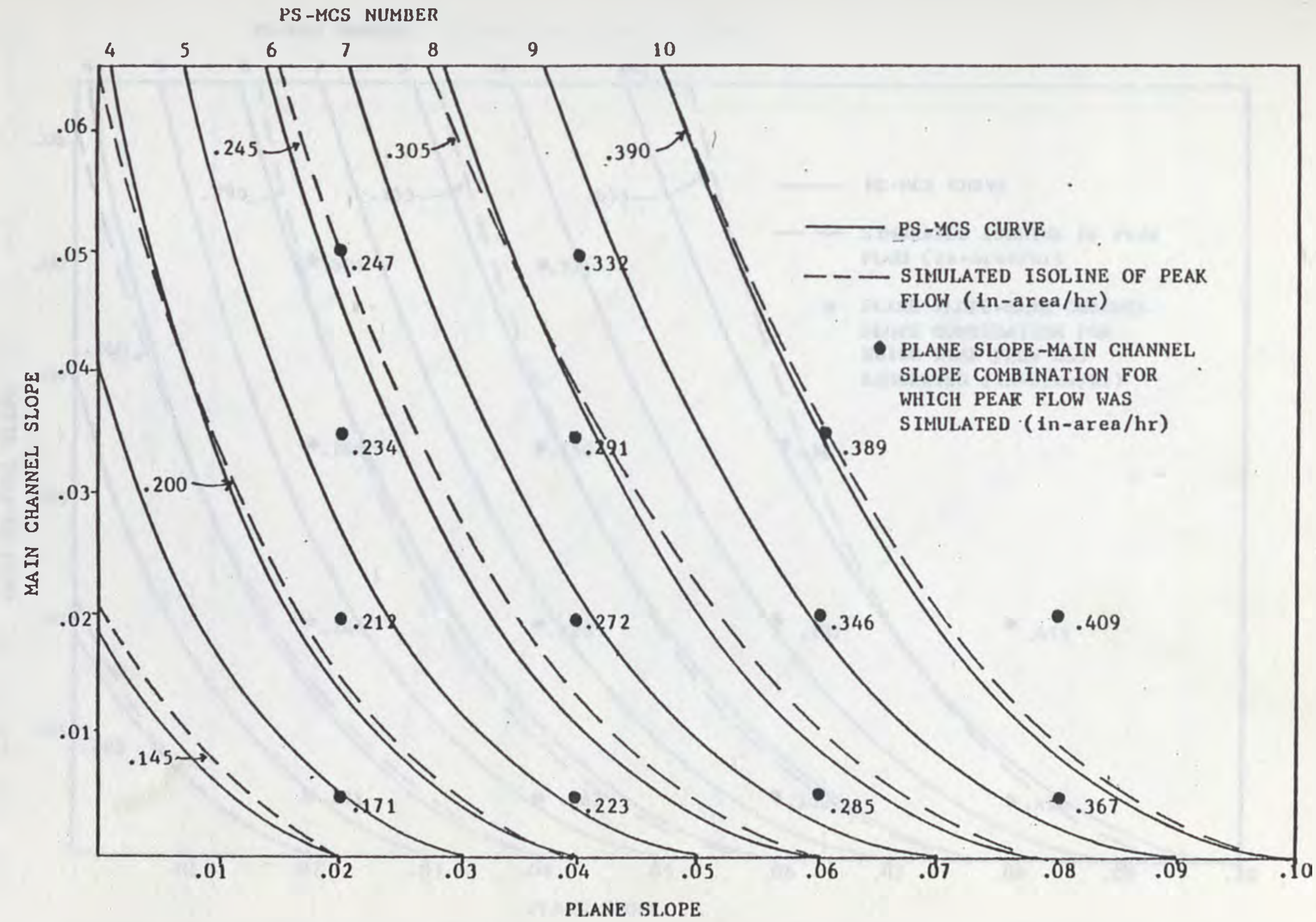


Figure 5.5. Set of PS-MCS curves and simulated isolines of peak flow for the simple unit area receiving a 6 in/hr design rainfall intensity input. Peak flow isolines are shown for PS-MCS numbers 2, 4, 6, 8, and 10.

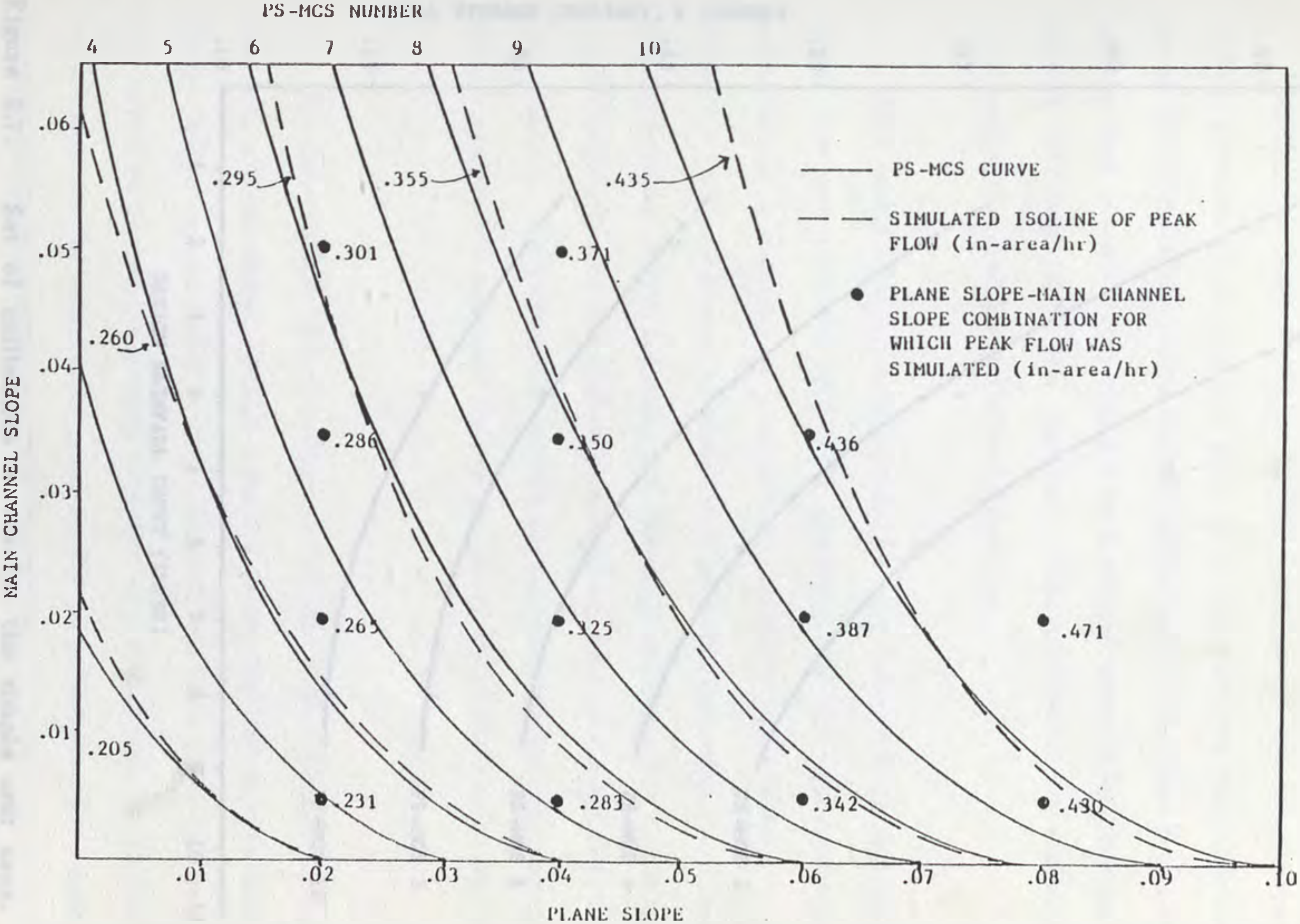


Figure 5.6. Set of PS-MCS curves and simulated isolines of peak flow for the simple unit area receiving an 8 in/hr design rainfall intensity input. Peak flow isolines are shown for PS-MCS numbers 2, 4, 6, 8, and 10.

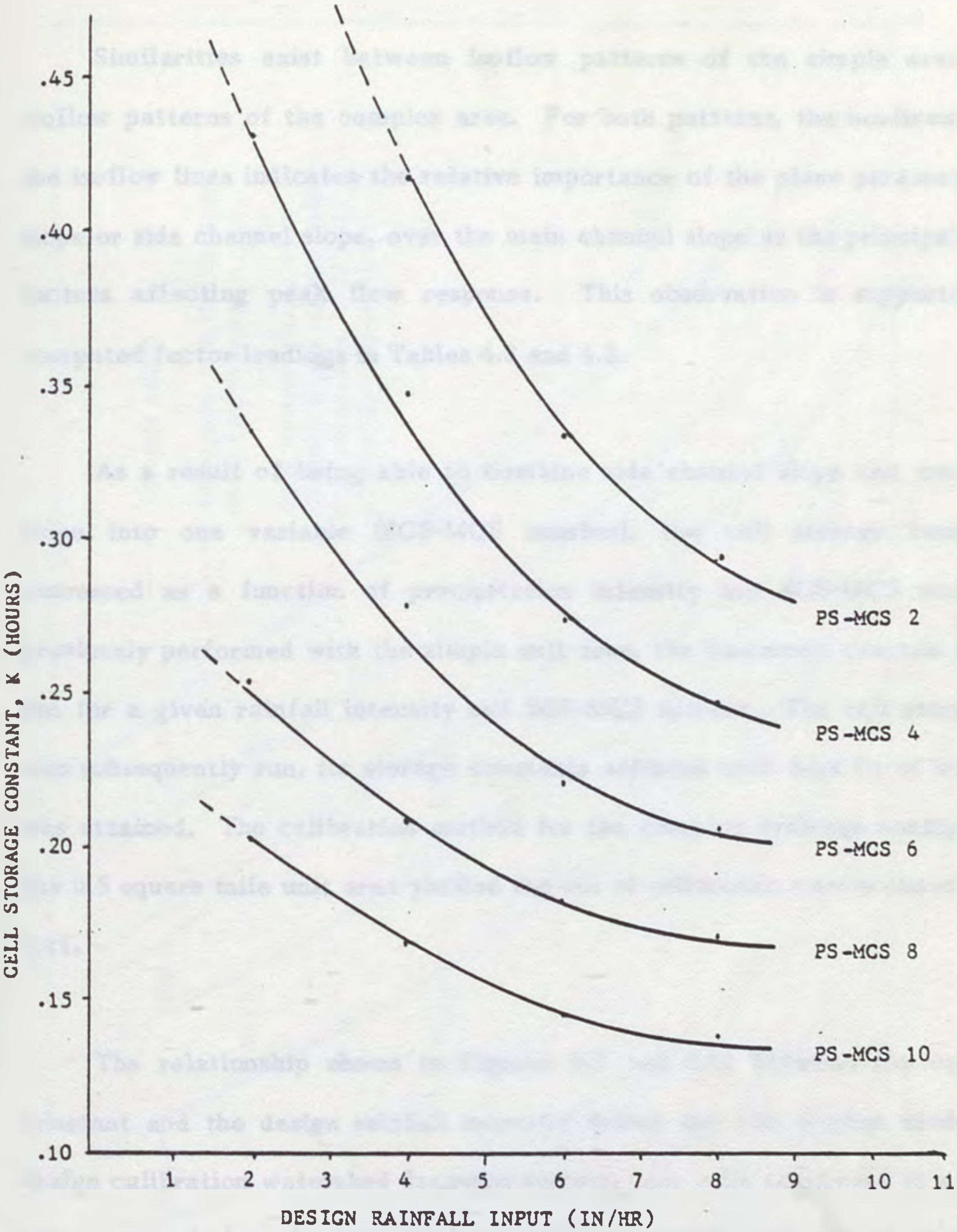


Figure 5.7. Set of calibration curves for the simple unit area. The cell storage constant is expressed as a function of design precipitation intensity and PS-MCS number.

slope (SCS-MCS) grids are illustrated for design precipitation intensity inputs of 3 inches/hour, 6 inches/hour, and 8 inches/hour in Figures 5.8 to 5.10, respectively.

Similarities exist between isoflow patterns of the simple area and the isoflow patterns of the complex area. For both patterns, the nonlinear trend of the isoflow lines indicates the relative importance of the plane parameters, plane slope or side channel slope, over the main channel slope as the principal hydraulic factors affecting peak flow response. This observation is supported by the computed factor loadings in Tables 4.2 and 4.3.

As a result of being able to combine side channel slope and main channel slope into one variable (SCS-MCS number), the cell storage constant was expressed as a function of precipitation intensity and SCS-MCS number. As previously performed with the simple unit area, the kinematic cascade model was run for a given rainfall intensity and SCS-MCS number. The cell storage model was subsequently run, its storage constants adjusted until best fit of hydrographs was attained. The calibration method for the complex drainage configuration of the 0.5 square mile unit area yielded the set of calibration curves shown in Figure 5.11.

The relationship shown in Figures 5.7 and 5.11 between the cell storage constant and the design rainfall intensity define the cell storage model for the design calibration watershed drainage system, four cells connected in a series. It was expected that the individual response of a single cell routed together with output responses of other cells would be able to predict flow for larger and more complicated drainage systems.

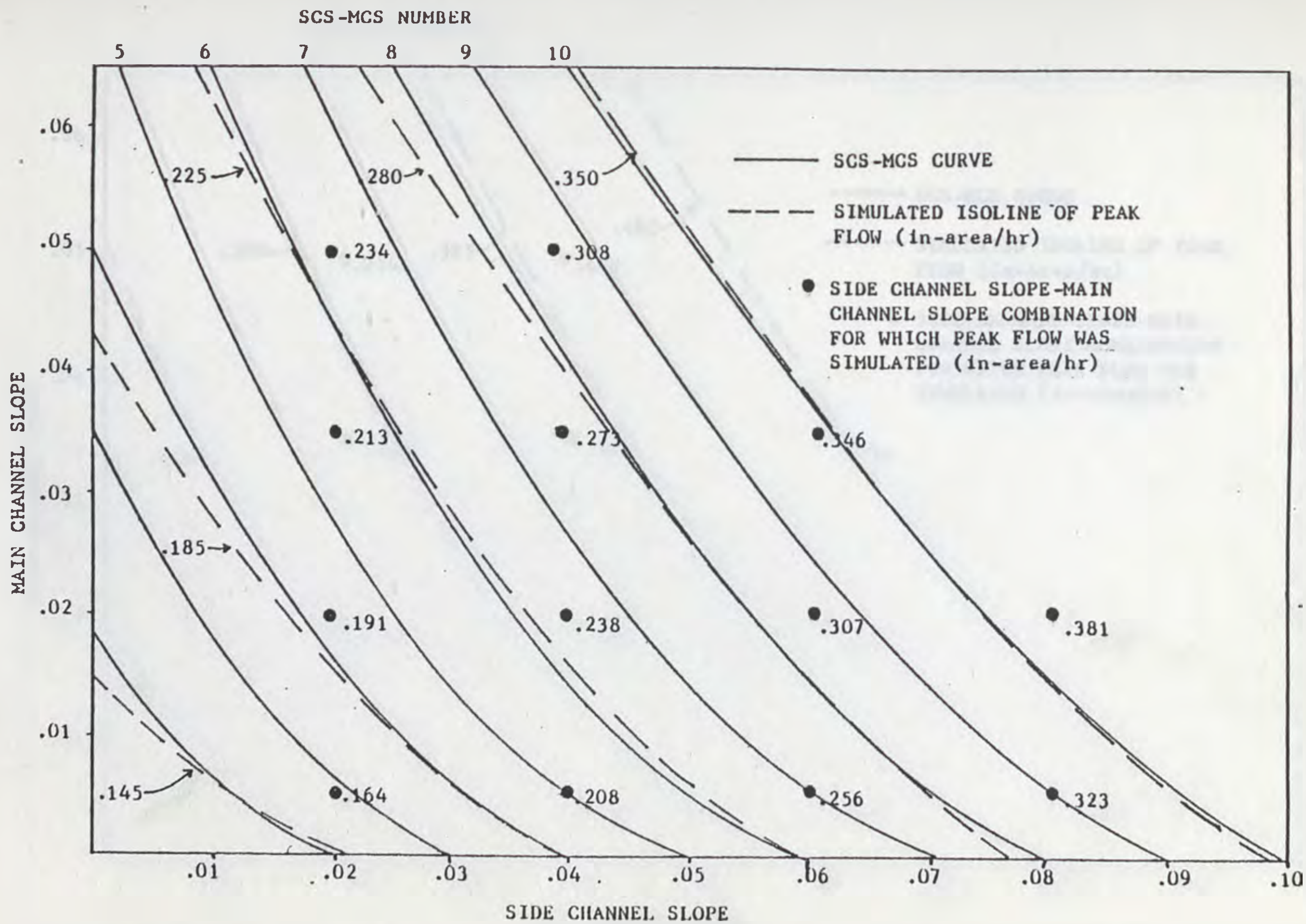


Figure 5.8. Set of SCS-MCS curves and simulated isolines of peak flow for the complex unit area receiving a 3 in/hr design rainfall intensity input. Peak flow isolines are shown for SCS-MCS numbers 2, 4, 6, 8, and 10.

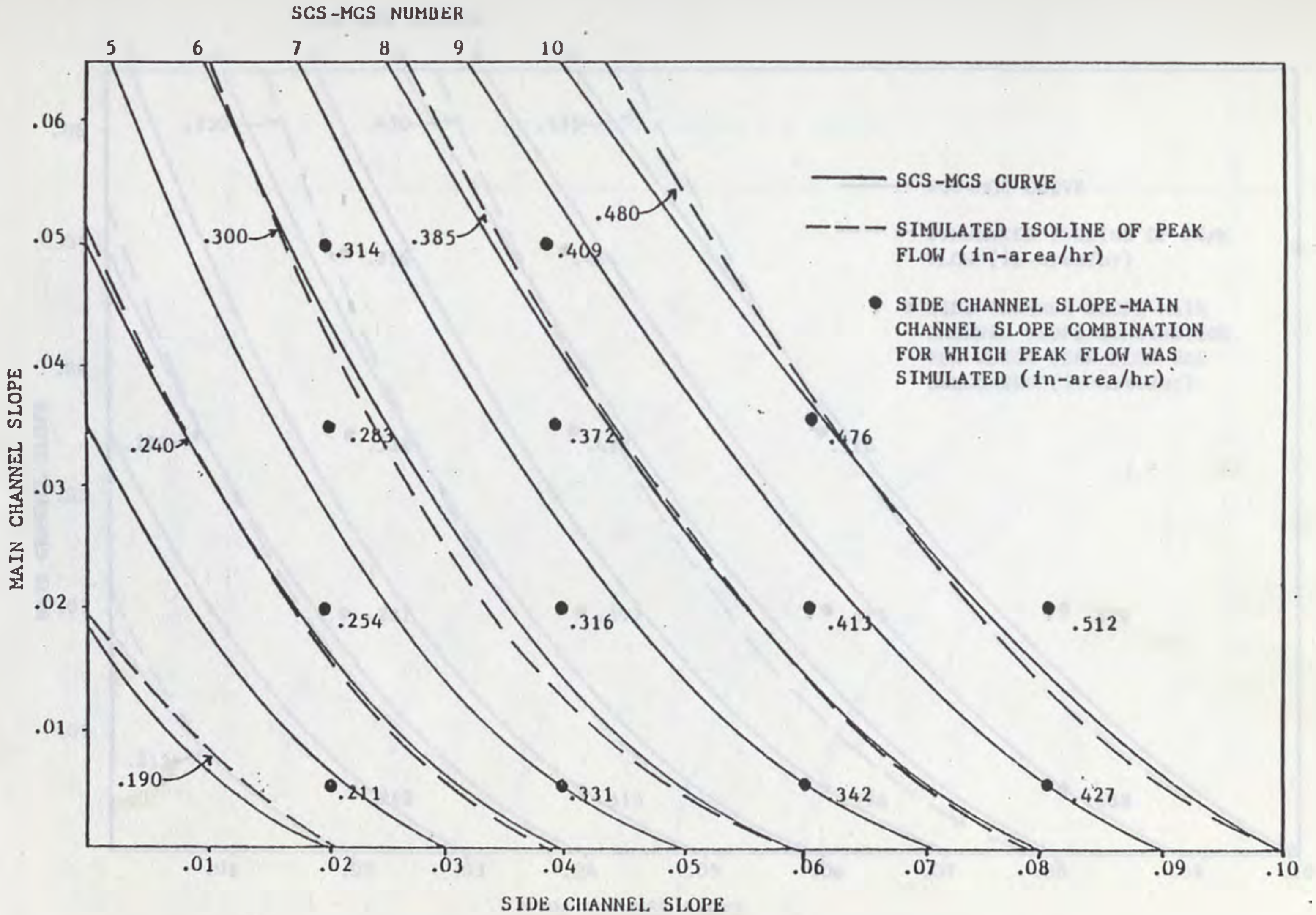


Figure 5.9. Set of SCS-MCS curves and simulated isolines of peak flow for the complex unit area receiving a 6 in/hr design rainfall intensity input. Peak flow isolines are shown for SCS-MCS numbers 2, 4, 6, 8, and 10.

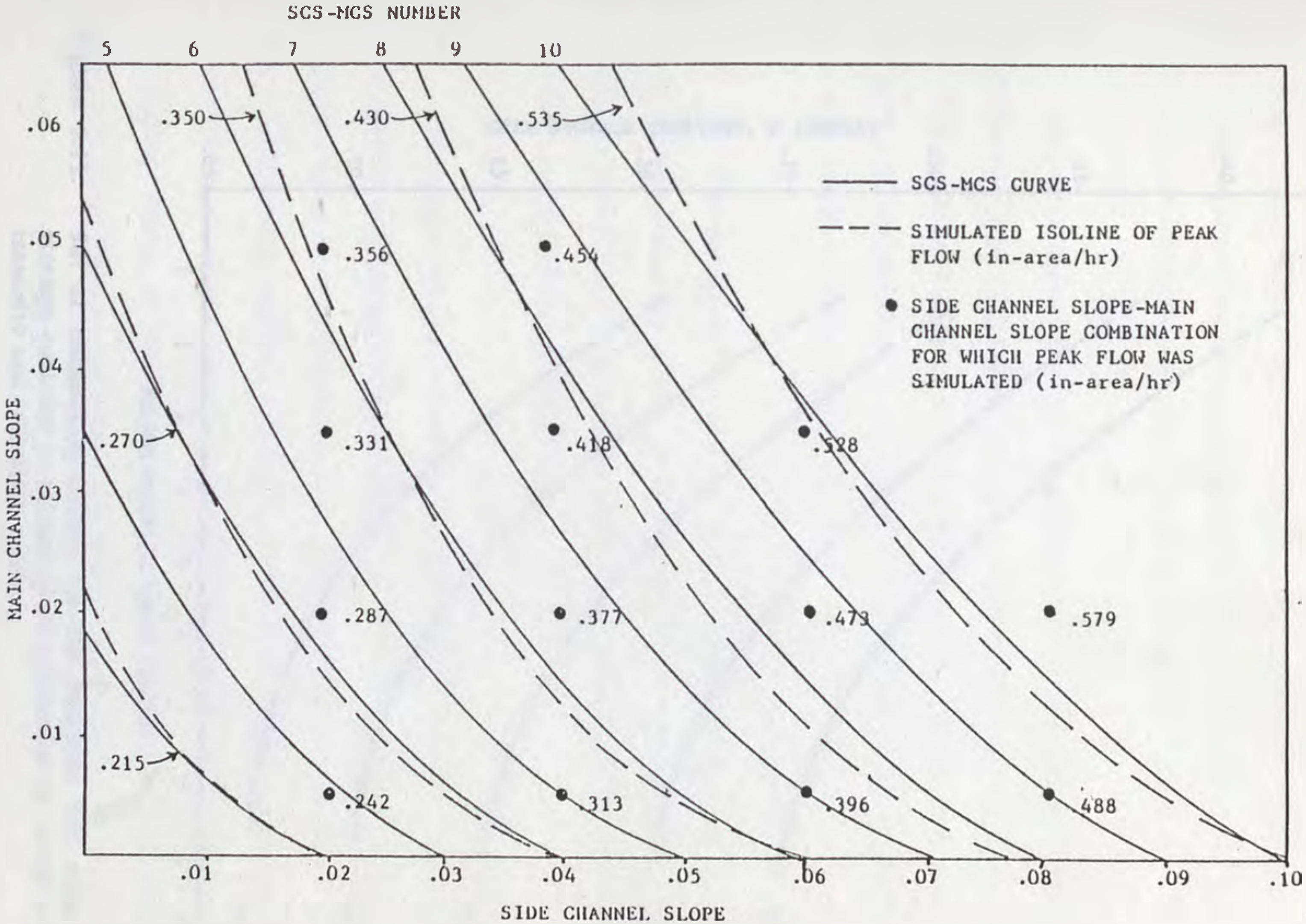


Figure 5.10. Set of SCS-MCS curves and simulated isolines of peak flow for the complex unit area receiving an 8 in/hr design rainfall intensity input. Peak flow isolines are shown for SCS-MCS numbers 2, 4, 6, 8, and 10.

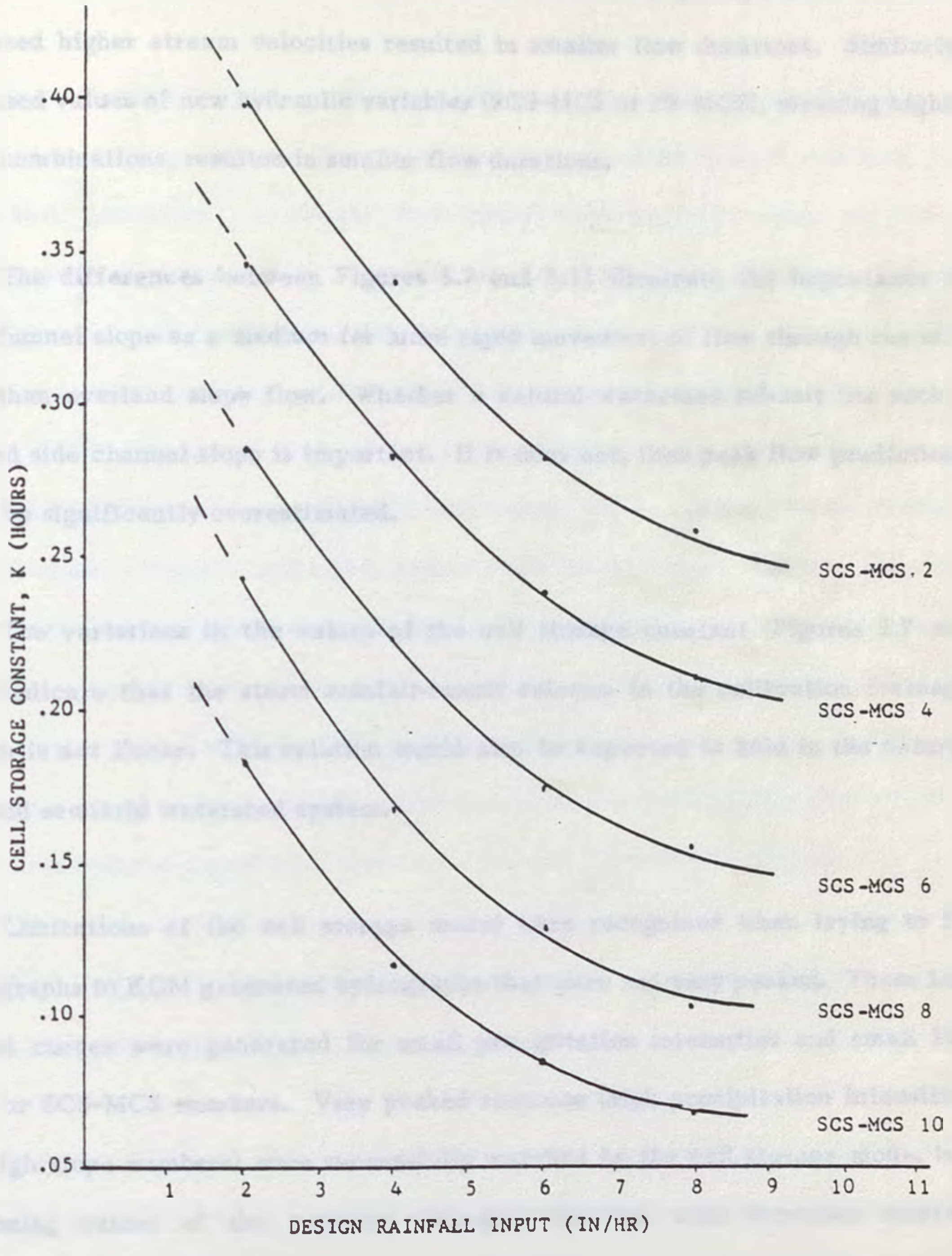


Figure 5.11. Set of calibration curves for the complex unit area. The cell storage constant is expressed as a function of design precipitation intensity and SCS-MCS number.

The relationship shown in Figures 5.7 and 5.11 was considered reasonable for the natural runoff system. In both sets of curves, as precipitation intensity increased higher stream velocities resulted in smaller flow durations. Similarly, increased values of new hydraulic variables (SCS-MCS or PS-MCS), meaning higher slope combinations, resulted in smaller flow durations.

The differences between Figures 5.7 and 5.11 illustrate the importance of side channel slope as a medium for more rapid movement of flow through the unit area than overland slope flow. Whether a natural watershed subunit has such a defined side channel slope is important. If it does not, then peak flow predictions could be significantly overestimated.

The variations in the values of the cell storage constant (Figures 5.7 and 5.11) indicate that the storm rainfall-runoff relation in the calibration drainage system is not linear. This relation would also be expected to hold in the natural arid and semiarid watershed system.

Limitations of the cell storage model were recognized when trying to fit hydrographs to KCM generated hydrographs that were not very peaked. These less peaked curves were generated for small precipitation intensities and small PS-MCS or SCS-MCS numbers. Very peaked response (high precipitation intensities and high slope numbers) were successfully matched by the cell storage mode, but increasing values of the optimum objective function with increased rainfall intensity input indicated that extreme inputs (greater than 12 inches/hour) could not be adequately matched.

5.5 Complex Unit Area: Interaction Between Side Channel Slope, Main Channel Slope, and Plane Slope

An apparent interaction among side channel slope, main channel slope, and plane slope may be inferred from the sensitivity analysis data (Table 4.3). A calibration procedure was sought that could successfully combine the three parameters into one variable. Research on this matter was performed but the results were not interpretable or successful, and are not reported. Work to reduce the three parameters into a combination of two variables resulted in a scheme to develop calibration curves that related a plane slope-side channel slope combination (PS-SCS number) to precipitation intensity for a specific value of main channel slope. Numerous sets of curves would be developed, one set for each incremental value of main channel slope. Although initial work on this method proved successful, completion of this calibration method was not pursued. Completion required approximately 400 runs of the kinematic cascade model, the time and cost of which was judged not cost effective for the expected minimal increase in explanation of total variation of the rainfall-runoff relation.

5.6 The Unit Area Without Precipitation Input: Interaction Between Main Channel Slope and Main Channel Roughness

The previously developed calibration methods considered the unit area as a watershed subunit catching an uniform rainfall input. This phenomenon, however, may not always take place in the natural watershed. Summer storms are often of limited areal extent and flow received in downstream areas may result strictly from upstream input and not from rainfall input within the area itself. For this case main channel factors are important because as the runoff leaves the source area, tributary plane and slope factors do not have any appreciable effect on flow.

The main channel factors of concern in this case are the main channel slope (MCS) and main channel roughness (MCR), expressed as the Manning roughness coefficient, n, (feet$^{1/6}$). Since the area does not receive rainfall, plane factors, including side channel slope, would not influence the rainfall-runoff relation. A relationship was sought between main channel slope, main channel roughness, and some description of flow input to the area.

The kinematic cascade model was run for a specific precipitation intensity and a variety of combinations of main channel slope and main channel roughness. The calibration method was altered from the procedure followed in the analysis of the simple and complex unit areas receiving rainfall. Rainfall was input only to the first area in series (area A) and hydrographs were simulated peak flow inputs into for downstream areas B, C, and D. Parameters that were kept constant during this method included main channel width and Horton's infiltration parameters. Peak flows generated for a specific area in series, a specific peak flow input, and the variety of main channel slope-main channel roughness combinations were then contoured.

Contoured isolines of peak flow tended to follow the pattern shown in Figure 5.12. This pattern was determined by plotting various values of a hypothetical main channel slope-main channel roughness (MCS-MCR) number, defined as:

$$\text{MCS-MCR Number} = (\text{MCS})^{1/2} / \text{MCR} \qquad (5.5)$$

This equation is adapted from Manning's equation:

$$Q = 1.49/n\ (S^{1/2})\ (P^{5/3}) \qquad (5.6)$$

where P is the wetted perimeter of the channel (feet). By assuming that P is constant and strictly considering peak flow, the MCS-MCR number can be assumed to represent isolines of peak flow. As indicated in Figures 5.12 to 5.14, the defined MCS-MCR number fits the simulated isolines of peak flow determined by the kinematic cascade model.

Variations in the patterns of peak flow isolines were attributed to decreased flow as a result of constant infiltration rates, and to the wetted perimeter not being constant. By method design, the channel width was held constant, and the depth of flow would be expected to vary with rate of flow.

A set of calibration curves, based on the above described relationships, were developed for the 0.5 square mile unit area without rainfall (Figure 5.15). In lieu of rainfall intensity input, calibration curves were developed that related MCS-MCR number to peak flow input to the area (inch-area/hour). Although adequate in successfully defining calibration curves for the unit area, flow input is of little use in the application of the calibration method to define storage constants of the cells of a natural watershed because flow input from one cell to another cannot be directly determined.

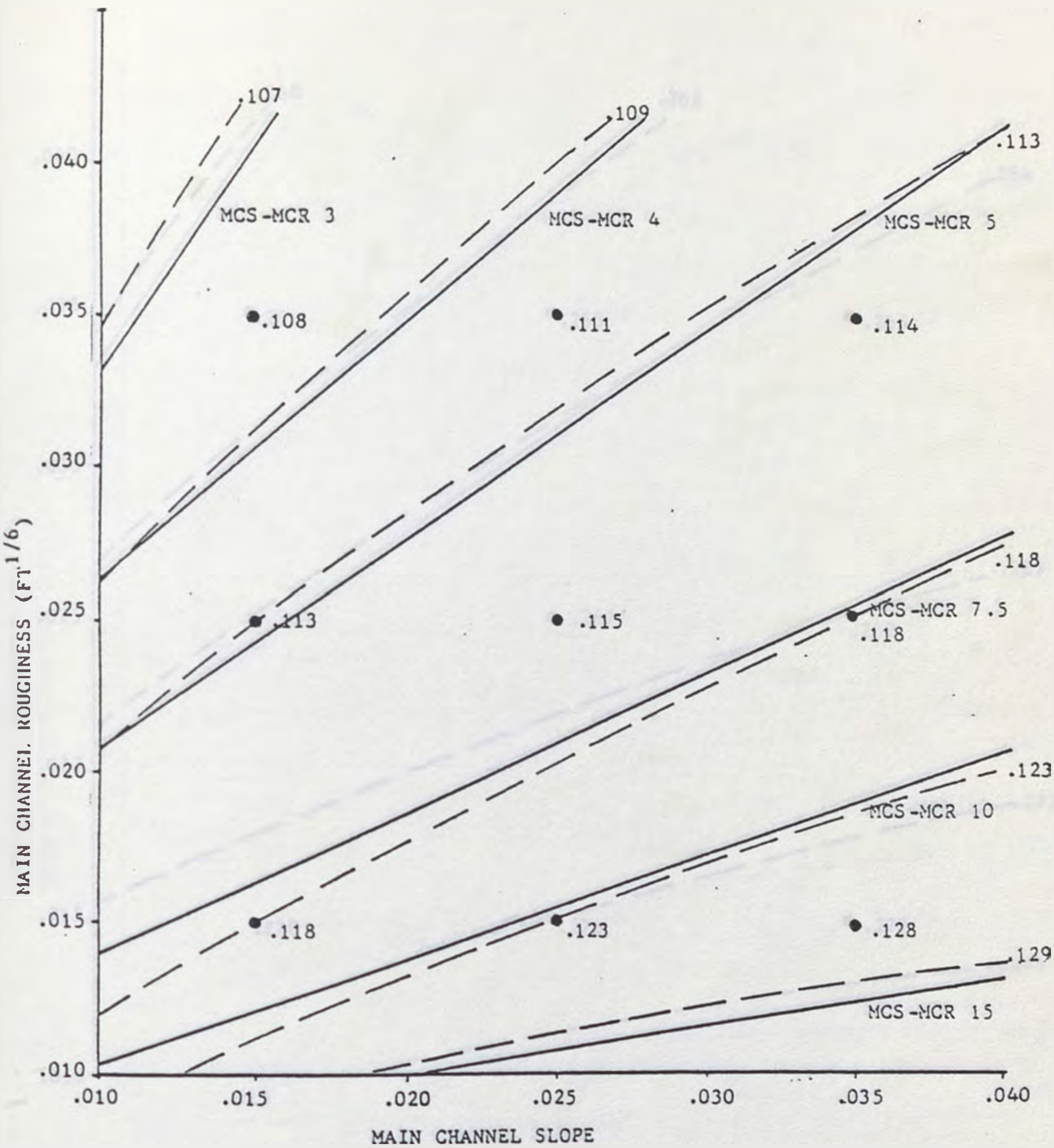


Figure 5.12. Set of MCS-MCR curves and simulated isolines of peak flow for the rainless unit area receiving a design channel flow input of .150 in-area/hr. Solid lines are MCS-MCR curves and hatched lines are corresponding simulated isolines of peak flow. Plotted points are main channel slope-main channel roughness combinations for which peak flows were simulated. All peak flow values are in units of in-area/hr.

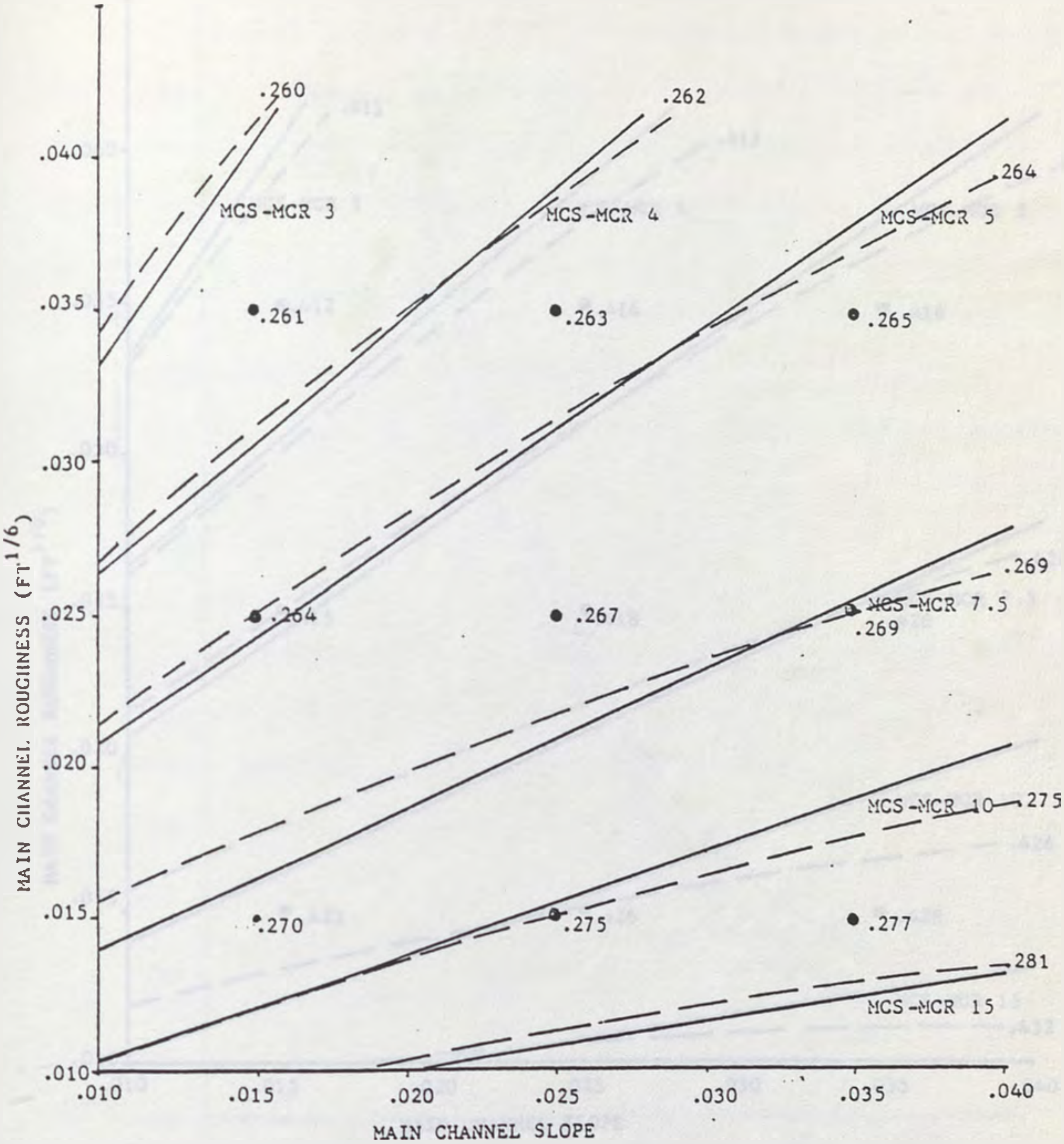


Figure 5.13. Set of MCS-MCR curves and simulated isolines of peak flow for the rainless unit area receiving a design channel flow input of .300 in-area/hr. Solid lines are MCS-MCR curves and hatched lines are corresponding simulated isolines of peak flow. Plotted points are main channel slope-main channel roughness combinations for which peak flows were simulated. All peak flow values are in units of in-area/hr.

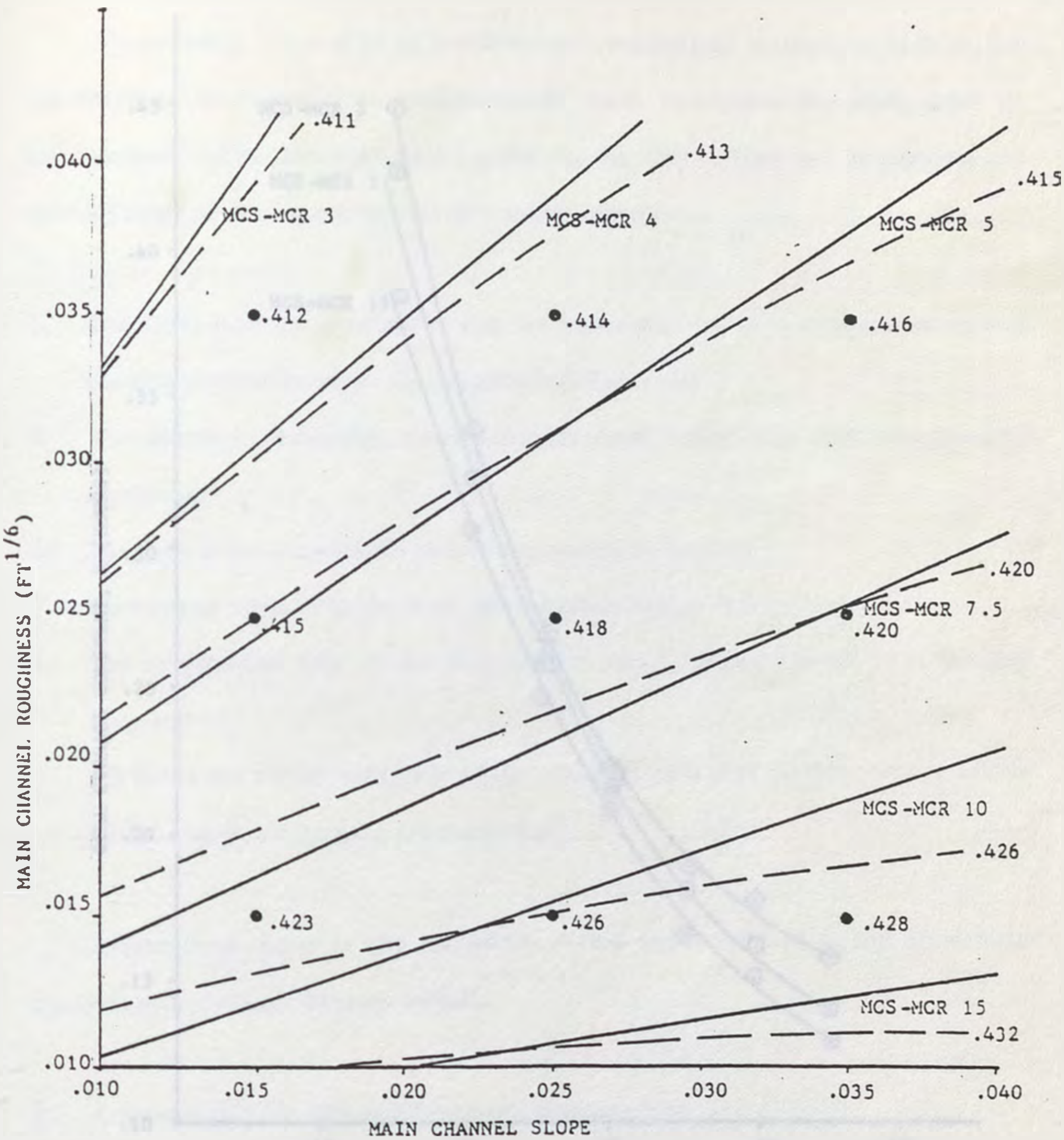


Figure 5.14. Set of MCS-MCR curves and simulated isolines of peak flow for the rainless unit area receiving a design channel flow input of .450 in-area/hr. Solid lines are MCS-MCR curves and hatched lines are corresponding simulated isolines of peak flow. Plotted points are main channel slope-main channel roughness combinations for which peak flows were simulated. All peak flow values are in units of in-area/hr.

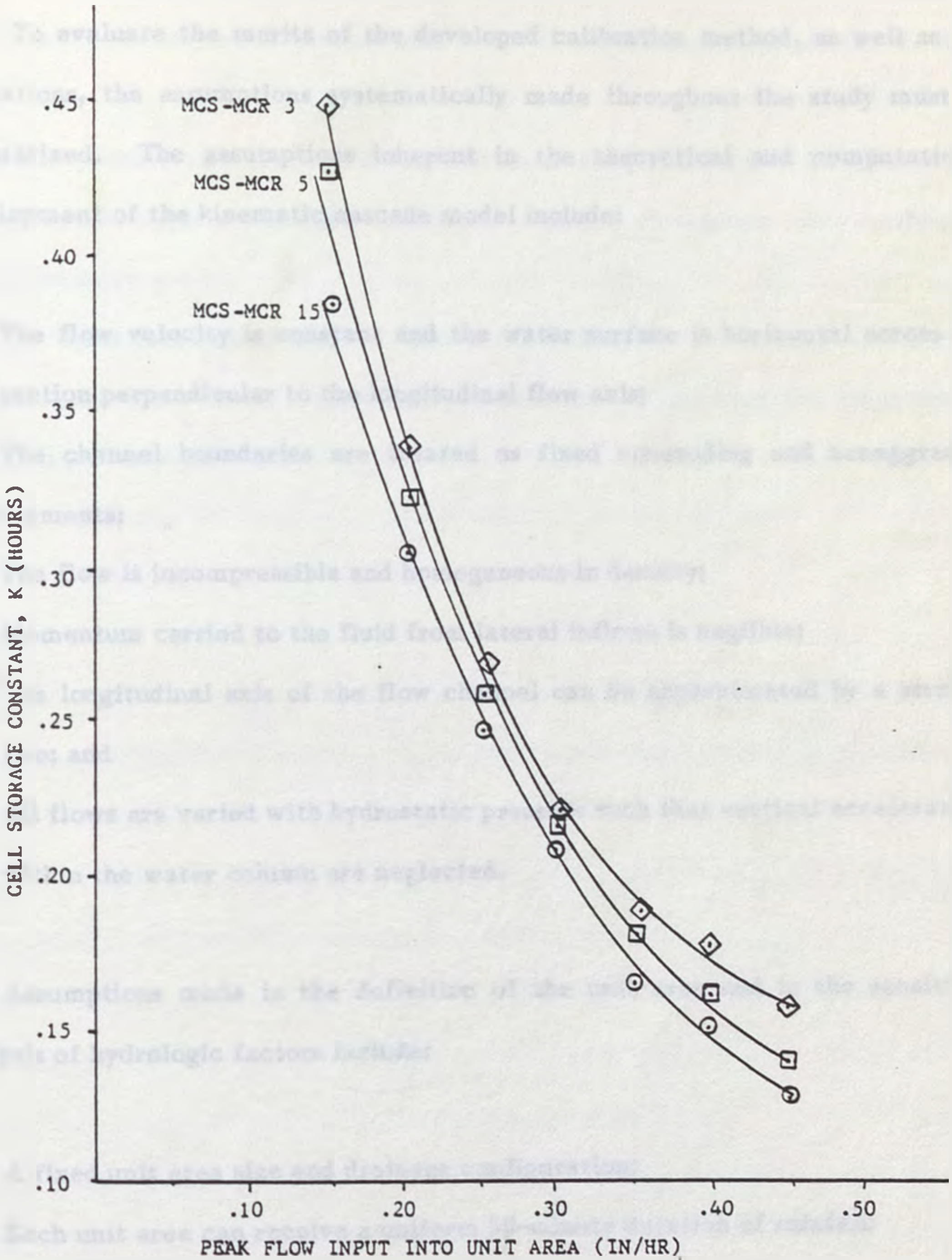


Figure 5.15. Set of calibration curves for the unit area not receiving rainfall input. The cell storage constant is expressed as a function of peak flow input into the unit area and the MCS-MCR number.

5.7 Summary of Assumptions Made in the Development of the Calibration Method

To evaluate the merits of the developed calibration method, as well as the limitations, the assumptions systematically made throughout the study must be summarized. The assumptions inherent in the theoretical and computational development of the kinematic cascade model include:

1. The flow velocity is constant and the water surface is horizontal across any section perpendicular to the longitudinal flow axis;
2. The channel boundaries are treated as fixed noneroding and nonaggrading elements;
3. The flow is incompressible and homogeneous in density;
4. Momentum carried to the fluid from lateral inflows is neglible;
5. The longitudinal axis of the flow channel can be approximated by a straight line; and
6. All flows are varied with hydrostatic pressure such that vertical accelerations within the water column are neglected.

Assumptions made in the definition of the unit area and in the sensitivity analysis of hydrologic factors include:

1. A fixed unit area size and drainage configuration;
2. Each unit area can receive a uniform 30-minute duration of rainfall;
3. Horton overland flow prevails with uniform infiltration determined by the Horton infiltration equation;
4. Overland flow occurs perpendicular to the channel element; and

5. Flow between unit areas occurs only through the main channel.

Finally, two important assumptions made in the calibration procedure include:

1. Those parameters determined by the sensitivity analysis to be of minimal influence upon peak flow are kept constant throughout the calibration procedure; and
2. For those parameters held constant in the calibration procedure, variations of one parameter during a simulated storm event will not vary the other watershed parameters.

CHAPTER 6

VALIDATION OF METHOD

The ultimate goal of this study is to develop a simple non-site specific method for predicting peak flows from extreme storm events in arid watersheds. By selecting the correct cell storage constant for each cell from the calibration curves developed in this study, reliable estimates of peak runoff should be obtained. The purpose of validation is to demonstrate that the model is capable of simulating historical hydrological events for which field data are available. In this section, comparisons between simulated cell model response and observed response are made.

The validation stage has two objectives. The first objective is to determine if a general method for predicting storm flow can be realized for ungaged arid and semiarid catchments. If significant discrepancies between observed and computed peak flow exist, then the second objective will be to isolate the particular hydrologic parameters that accounted for the apparent differences.

6.1 Parameter Measurement

Measurements of main channel slope, side channel slope, and plane slope as well as 30 minute precipitation intensity were required to determine specific cell storage constants for each cell in the modeled watershed. All morphologic measurements were taken from standard 1:24,000 scale topographic maps prepared by the U. S. Geological Survey.

Main channel slope (MCS) and side channel slope (SCS) were determined by a weighted average method:

$$MCS = \frac{\Sigma(S_i L_i)}{L_t} \qquad (6.1)$$

Where L_i is the channel segment length, S_i is the channel segment slope, and L_t is the total channel length. Individual segments were delineated as reaches of apparently similar slope. For the determination of side channel slope, L_t represents the total length of all side channels in the unit area cell.

Plane slope was determined for each cell by a similar weighted average method:

$$PS = \frac{\Sigma(S_a A_a)}{A_t} \qquad (6.2)$$

where S_a is the average slope of the overland area on either side of the main channel, A_a is the area of each hillside, and A_t is the total area of the cell. A_t equals 0.5 square miles, the constant area of the defined unit area. For convenience S_a was determined by a simple relief ratio rather than a more tedious contour average technique. For the small S_a areas studied (approximately 0.25 square miles), differences in slopes determined by the two methods were very minimal.

For each modeled storm, the 30 minute rainfall intensity input to each cell was determined from extreme storm event records tabulated by the Agricultural Research Service, U. S. Department of Agriculture (1964-1972).

Rainfall on all tested watersheds was described by one hyetograph representative of the spatial and temporal storm pattern. To properly correlate rainfall and runoff, Osborn and others (1971a) showed that three evenly spaced rain gages are needed for a one square mile watershed and five evenly spaced gages are required for a 10 square mile watershed. For watersheds larger than 10 square miles, the reliability of a single hyetograph rainfall description decreases rapidly with increasing watershed area. Although the cell model has the capability for accepting distributed rainfall patterns, one hyetograph for each cell, limited storm data prevents this important input.

The information required to model each experiemental watershed considered in this study is listed in Appendix A. This information includes a generalized map of the watershed, description of the watershed, the cell drainage network, and values of plane slope, main channel slope, and side channel slope. Information on the 53 storm events modeled in this study are listed in Appendix B.

For each watershed tested, cells were placed in a manner such that the area was represented by a channel segment and intersecting slopes on either side of the channel. The cells were connected to best mimic the natural drainage network. As expected, not all cells covered simple plane and channel combinations. Topographic complexities in some watershed areas, as with subareas not bisected by any discernible channel, were unavoidable and expected to contribute to any error in the prediction of peak flow. Another expected problem was the fitting of large rectangular cells in rounded watersheds. A perfect fit of modeled cells within the boundaries of the catchments could not be performed and resulting errors may have been incurred because of this.

For each delineated cell, the calculated main channel slope and plane slope were plotted on the plane slope–main channel slope grid (Figure 5.4) to determine the corresponding PS-MCS number. The PS-MCS number and the calculated 30 minute rainfall intensity were then plotted on the simple unit area calibration curve to find the corresponding cell storage constant. The cell storage constant determined for each cell was then input into the cell storage model and the model was run to simulate a runoff hydrograph for the particular rainfall intensity. The same procedure was used to determine the cell storage constant for each complex unit area from calculated values of main channel slope, side channel slope, and rainfall intensity.

6.2 Comparison of Rainfall-Runoff Data and Results

Peak flow values predicted by cell storage model for both the simple and the complex unit area calibration methods are listed along with observed flow in Table 6.1. The data are also illustrated in Figures 6.1 and 6.2.

Perfect correlation between observed and simulated peak flows, plotted on the x and y axis respectively, would yield a line with a slope of 1 and y axis intercept of 0. To estimate the degree of interrelation between these two variables a measure of correlation can be used. The correlation coefficient, r, is defined as a ratio of the covariance of two variables to the product of their standard deviations (Davis, 1973). An r value of 1 indicates a perfect positive relationship between two variables. The correlation coefficient and slope of the regression line are used to make comparison judgements of the validity of the calibration methods.

STORM EVENT	SIMULATED PEAK FLOW (IN/HR) SIMPLE METHOD	SIMULATED PEAK FLOW (IN/HR) COMPLEX METHOD	OBSERVED PEAK FLOW (IN/HR)
WALNUT GULCH WATERSHED W-3			
1	.127	.162	.052
2	.091	.110	.038
3	.102	.130	.064
4	.091	.110	.026
5	.102	.130	.004
6	.124	.155	.132
7	.116	.149	.610
8	.100	.127	.003
9	.102	.130	.020
10	.124	.155	.054
WALNUT GULCH WATERSHED W-8			
11	.264	.305	.112
12	.124	.156	.220
13	.299	.348	1.110
14	.228	.274	.147
15	0	0	.019
16	.105	.132	.025
17	.191	.227	.113
18	.084	.102	.127
19	.202	.242	.332
20	.179	.202	.050
21	.105	.132	.098
WALNUT GULCH WATERSHED W-15			
22	.200	.238	.111
23	.255	.297	.134
24	.191	.227	.056
25	.207	.234	.178
26	.116	.142	.059
27	0	0	.145
28	.160	.183	.211
29	0	0	.020
SONORA WATERSHED S-10			
30	.172	.195	.809
31	.105	.121	.112
32	.063	.074	.026
33	0	0	.279
SONORA WATERSHED S-11			
34	0	0	.095
35	.218	.260	.391
36	.185	.223	.310
37	.115	.136	.132
38	.185	.223	.446
SONORA WATERSHED S-12			
39	.116	.135	1.203
40	.176	.232	.850
41	.121	.150	.283
42	.121	.150	.278
43	0	0	.321
CHICKASHA WATERSHED C-611			
44	.191	.227	.137
45	.201	.248	.493
46	0	0	.012
47	.099	.118	.050
48	.099	.118	.124
49	0	0	.013
50	0	0	.020
51	.099	.118	.106
52	.221	.264	.100
53	.221	.264	.051

Table 6.1. Peak flow values predicted by the cell storage model for the simple and the complex unit area calibration methods.

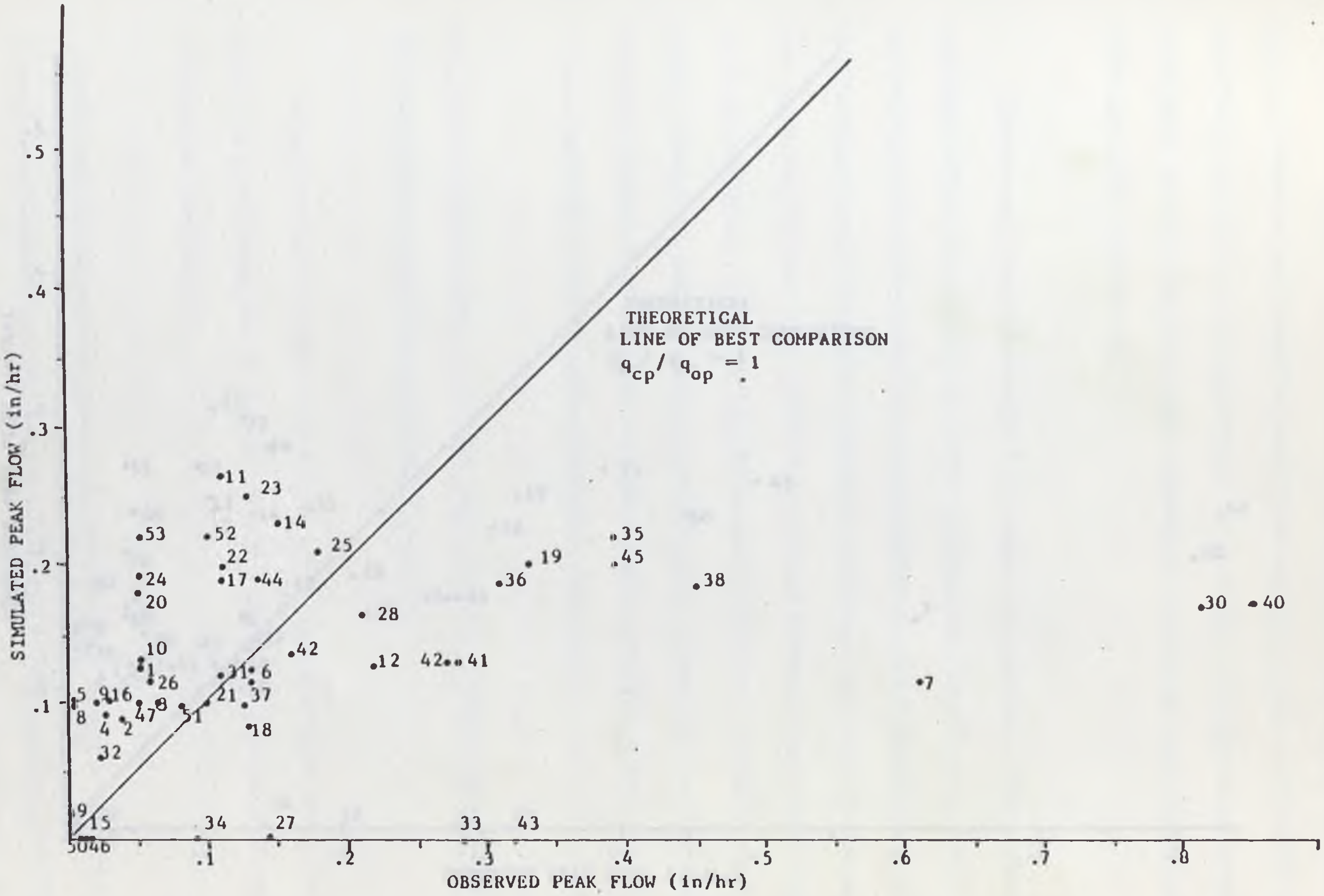


Figure 6.1. Plot of simulated peak flow and observed peak flow for 53 storm events modeled using the simple unit area cell storage model calibration method.

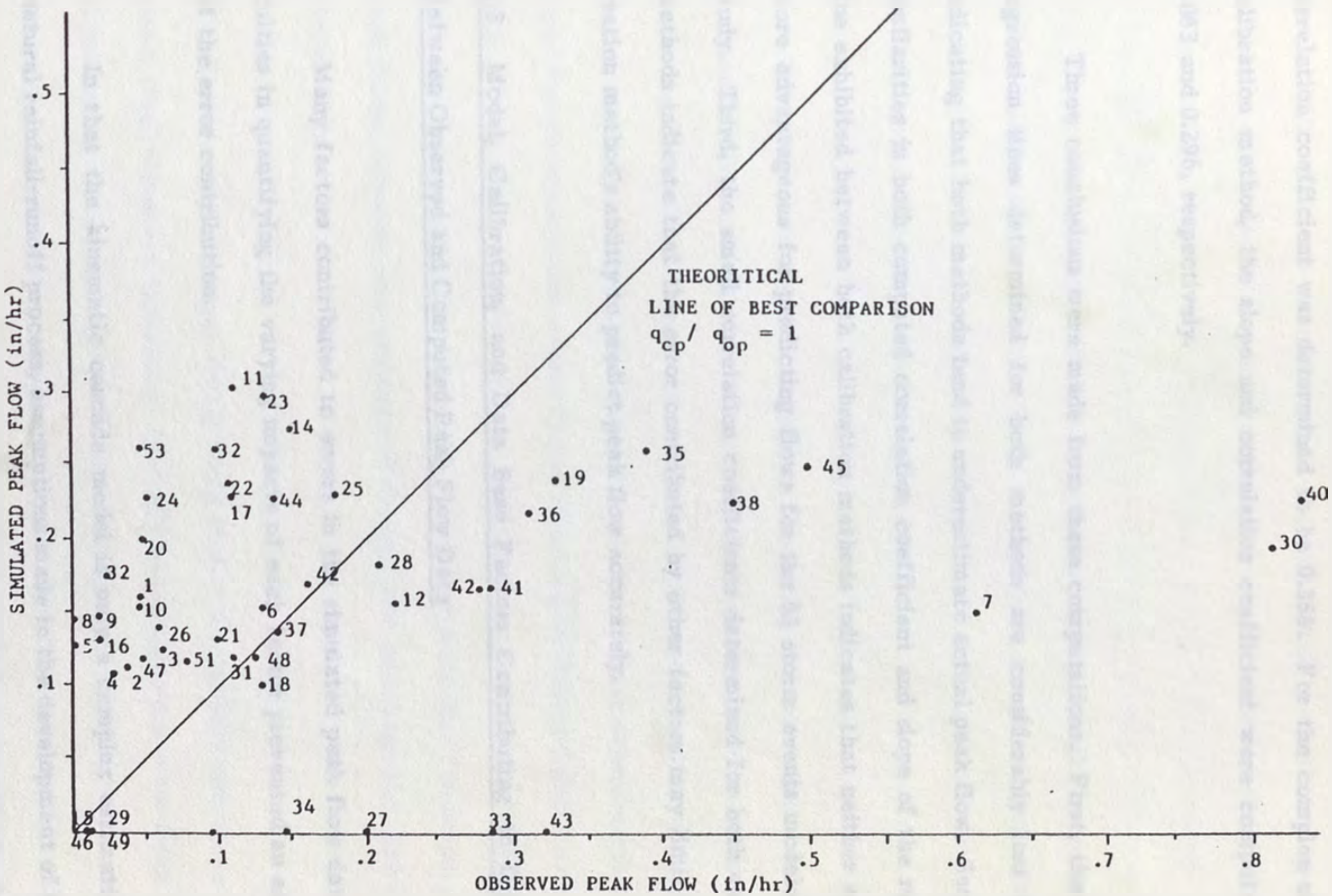


Figure 6.2. Plot of simulated peak flow and observed peak flow for 53 storm events modeled using the complex unit area cell storage model calibration method.

For the simple unit area calibration method, the slope of regression line between observed and computed peak flows was determined to be 0.102 and the correlation coefficient was determined to be 0.358. For the complex unit area calibration method, the slope and correlation coefficient were computed to be 0.083 and 0.296, respectively.

Three conclusions were made from these computations. First, the slope of regression lines determined for both methods are considerably less than 1.0 indicating that both methods tend to underestimate actual peak flow. Second, the similarities in both computed correlation coefficient and slope of the regression line exhibited between both calibration methods indicates that neither method is more advantageous for predicting flows for the 53 storm events modeled in this study. Third, the small correlation coefficients determined for both calibration methods indicate that the error contributed by other factors may limit the calibration method's ability to predict peak flow accurately.

6.3 Model, Calibration, and Data Base Factors Contributing to Differences Between Observed and Computed Peak Flow Data

Many factors contributed to errors in the simulated peak flow data. Difficulties in quantifying the varying impacts of each factor prevented an assessment of the error contribution.

In that the kinematic cascade model is only a complex estimation of the natural rainfall-runoff process, assumptions made in the development of the model or its application for calibration purposes may result in errors in simulated peak flows. Assumptions made in the development of the kinematic cascade model and the calibration method are summarized in Chapter 4. Error incurred in generating the synthetic data are transmitted to the calibration curves developed in this study, and subsequently incorporated into the peak flow simulations of the cell storage model.

The calibration method did not include the hydrologic parameters that exhibited only minimal influence on the rainfall-peak runoff relation. The collective influence of these factors, although perceived as small, had some effect on the developed calibration curves.

The problem of rainfall variability, especially in large watersheds, tends to overwhelm the problems of the variability of other watershed parameters. When describing the rainfall input to a watershed of some extent with one hyetograph, spatial variability of the actual rainfall would likely cause errors in runoff prediction. For example, storm events 03 and 07 falling on Walnut Gulch Watershed W-3 have similar characteristics of total rainfall, 30 minute peak intensity, time to peak, and antecedent moisture conditions (see Appendix B). The storm generated peak flows, however, are strikingly different, .064 inch/hour and .610 inch/hour, respectively.

Beven and Hornberger (1982) found that in a relatively homogeneous catchment, total volume of input into a spatially variable pattern is far more important in predicting stream hydrographs than assessing storm intensity patterns. Limited rain gage data, however, would likely prevent such a distributed volume from being accurately determined. Rainfall variability was considered the single most important factor accounting for the variability of simulated peak flows, although no quantitative measure of this variability could be made.

The size of the watershed may affect the response of the cell storage model, not just by the effects of rainfall variability, but by the variations of hydraulic parameters with increasing size of the watershed. In most arid and semiarid watersheds, the surface water yield generally decreases with watershed area. This trend is due to large transmission losses in the major channels of the drainage network. These downstream channel segments are often larger than the designed channels of the unit areas. Without a special loss function, the unit area cannot account for such large transmission losses. As a result, predicted peak flows tend to be larger than observed. This observation, however, is not supported by the data. For the largest watershed tested in this study, the 16.9 square mile Sonora Watershed S-11, all observed peak flow data were considerably higher than the corresponding simulated peak flows. Two of the five storm events tested for watershed S-11 exhibited antecedent moisture conditions prior to runoff producing rainfall, possibly causing the observed disparity. In general, there was no observed relationship between watershed size and differences between observed and simulated flows. Considering the data, an areal limit to a watershed that could be successfully modeled by the calibration method should be based more on the availability of rainfall information than on size dependent watershed characteristics.

The advantage of developing a calibration method for arid watersheds is that antecedent moisture is generally not present in the basin and can be eliminated from the list of potential influential factors affecting peak runoff. When present, antecedent moisture tends to cause simulated peaks to be less than observed peaks.

An antecedent moisture condition is defined as the summation of the five-day precipitation before runoff producing storm, and is grouped into three classes by the Soil Conservation Service (1971). Each group has a range of values depending on the growing season.

To detect any effect of antecedent moisture on model response, storms falling on watersheds exhibiting antecedent moisture greater than 1.4 inches (AMC II) were isolated (Figure 6.3). Points plotted below the line of best comparison, indicating lower simulated peak flows than observed, could be indicative of the effects of prestorm moisture. The observed position of the points support this discussion. Eliminating the antecedent moisture storms from the total sample, however, improved the comparison statistics only slightly, resulting in an r value of 0.371 and a slope of 0.135 for the simple calibration method.

Differences in gross geomorphologic characteristics among watersheds tested in this study may have had some effect on the disparity between observed and simulated peak flow data. As shown in Figure 6.1, simulated peak flow modeled for storm events of the group of Walnut Gulch Watersheds (events 1 through 28) generally overestimate observed peak flow, while simulated peak flow for storm events on the Sonora Watershed group generally underestimate observed peak flow. This trend is attributed to differences in soil infiltration properties. Soils overlaying the Sonora Watershed are primarily clays that exhibit more runoff potential than the coarser sands that overlie the Walnut Gulch Watersheds. The

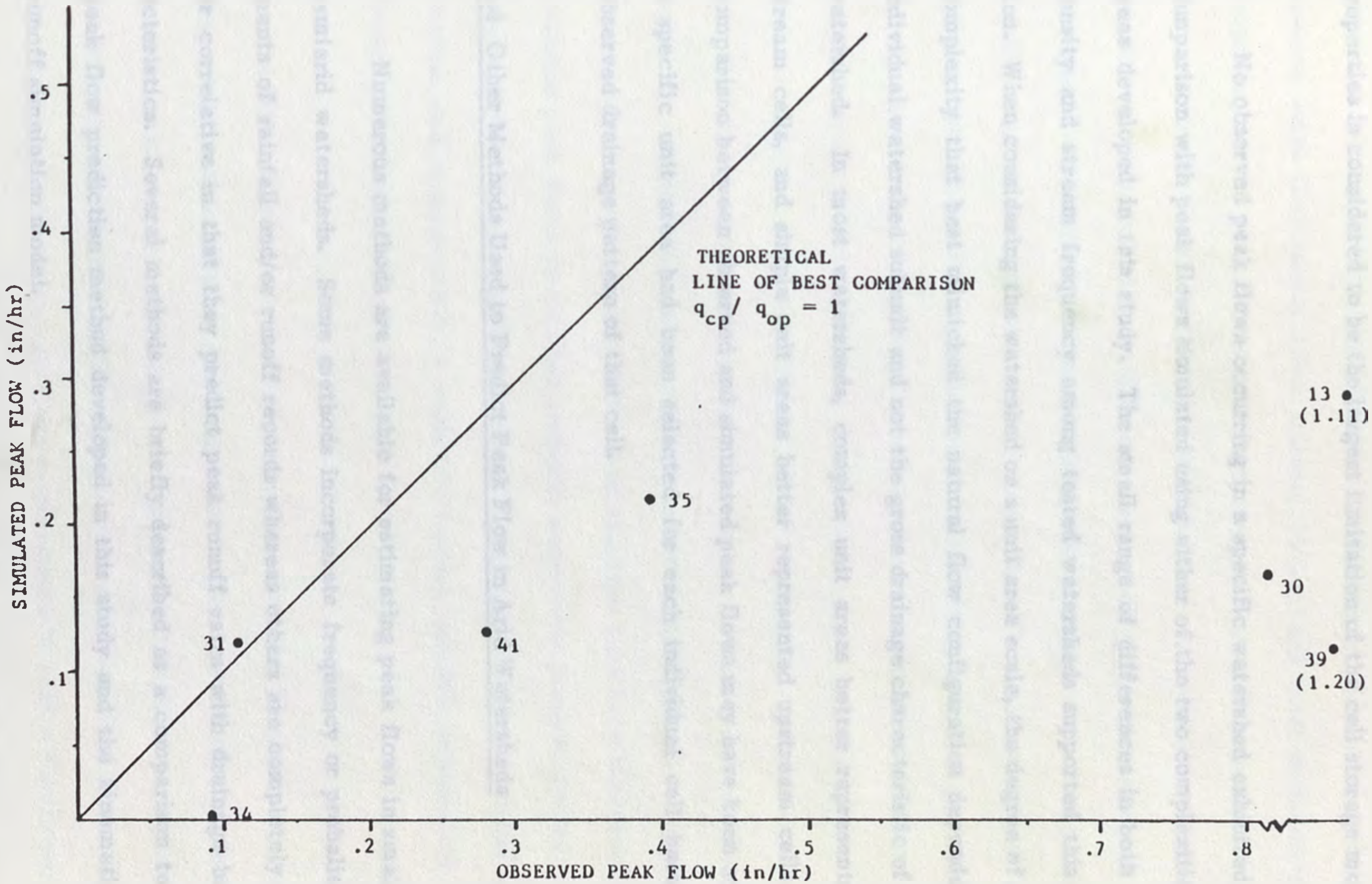


Figure 6.3. Plot of simulated peak flow and observed peak flow for 8 storm events having antecedent moisture conditions. Storm events were modeled using the simple unit area calibration method.

inability of the calibration method to consider spatial variations of infiltration properties is considered to be the largest limitation of the cell storage model.

No observed peak flows occurring in a specific watershed exhibited a better comparison with peak flows simulated using either of the two complexities of unit areas developed in this study. The small range of differences in both drainage density and stream frequency among tested watersheds supported this observation. When considering the watershed on a unit area scale, the degree of unit area complexity that best mimicked the natural flow configuration depended on the individual watershed subunit and not the gross drainage characteristic of the total watershed. In most watersheds, complex unit areas better represented downstream cells, and simple unit areas better represented upstream cells. Better comparison between observed and simulated peak flows may have been achieved if a specific unit area had been selected for each individual cell based on the observed drainage pattern of that cell.

6.4 Other Methods Used to Predict Peak Flow in Arid Watersheds

Numerous methods are available for estimating peak flows in small arid and semiarid watersheds. Some methods incorporate frequency or probalistic treatments of rainfall and/or runoff records whereas others are completely empirical or correlative in that they predict peak runoff rates with drainage basin characteristics. Several methods are briefly described as a comparison to both the peak flow prediction method developed in this study and the kinematic cascade runoff simulation model.

Frequency analysis consists of interpreting a past record of hydrologic events in terms of future probabilities of occurrence. Many frequency analysis methods exist (Dalrymple, 1960; Benson, 1964a), and most methods entail the linearizing of the cumulative probability curve of peak flow occurrences. Peak flow magnitudes for a specific recurrence interval are then determined by interpolation or extrapolation. The advantages of frequency analysis are the convenient calculation of the desired peak discharge and the minimal data requirements of strictly peak discharge records. The disadvantage of frequency analysis methods are the dependence upon a relatively complete period of record, the site specificity of the data, and the potential errors incurred from non-pure randomness of the records.

Reliable peak flow estimates often can be obtained within a homogeneous region by statistically correlating dependent hydrologic variables with other causitive factors. Predictive methods of this type have been successfully used to estimate peak flows in arid and semiarid watersheds (Benson, 1964b; Osborn and others, 1971b; Murphey and others, 1977). Data requirements include the identification and measurement of causitive factors and the compilation of ample stormflow hydrographs.

Additional or more reliable information can often be obtained by combining frequency analysis of peak discharge with regional correlation of flood causing factors. An accepted method of this type is the U. S. Geological Survey Index-Flood Method (Dalrymple, 1960). The method uses statistical data but combines them in graphical summaries. Data requirements include a significant period of record for accurate flood frequency curves plus watershed and climatic measurements. The disadvantage of the method is the extensive discharge data required for interbasin comparison.

A conjunctive use of recurrence frequency distributions of storms and empirical watershed relationships have been developed by Moore (1976). Streamflow records were used to define empirical relationships between 10-year peak flow events and elevation zones within hydrologically homogeneous regions in Nevada. Flood flows for other recurrence intervals can be determined from power functions of the 10-year recurrence interval relationship. The advantages of the method are those described in the frequency analysis methods. Limitations of the method include the site specificity of the developed relationship, and the inability to reliably predict peak flows for drainage basins located on valley floors. Also of note are similar empirical techniques for relating 10-year recurrence interval floods with channel geometry measurements to obtain discharge estimates for watersheds in Nevada (Moore, 1976).

A simple method for peak flow estimation in small rural watersheds where detailed hydrologic studies are not justified is the Cook Method (Soil Conservation Service, 1971). The technique employs an empirical relationship between drainage area and peak flow with modifications for climate, relief, infiltration and vegetal cover. Climate and watersheds parameters are derived from a general survey of morphologic characteristics of a particular watershed. The disadvantage of the method is the limited accuracy of the peak flow estimate due to generalized watershed characteristics and the 2,500 acre basin size limit of the method.

A more detailed empirical treatment of rainfall-peak runoff relationship is the Soil Conservation Service peak flow determination method (Soil Conservation Service, 1971). The method was developed for homogeneous watersheds on which the land use and soil type may be represented by a single parameter termed the runoff curve number. The runoff curve number is a third variable in a graph of rainfall versus runoff (Chow, 1964). Although considered more reliable than the Cook Method, the Soil Conservation Service method is subject to errors in peak runoff prediction due to a single parameter representation of watershed response. A more detailed discussion of the method is given in Chapter 6.5.

6.5 Comparison of Cell Storage Model Calibration Method to SCS Peak Flow Determination Method

A more revealing test of validity of the cell storage model calibration method is made by comparing the method to the Soil Conservation Service standard peak flow determination method. The SCS method is based on known precipitation and certain watershed characteristics, such as the indices of the soil-cover complex and antecedent moisture (Soil Conservation Service, 1971).

The hydrologic soil group is divided into four classes based on infiltration characteristics. Cover groups are determined from land use and condition of treatment. The antecedent moisture condition is the five-day summation of pre-storm rainfall and is divided into groups based on growing season.

Knowing the soil-cover complex and antecedent moisture condition, a corresponding runoff curve number is determined from standard SCS curves. Total runoff is graphically determined from the known precipitation volume and runoff curve number. The curve number runoff volume relationship is based on a watershed size of no more than 2,500 acres. Peak flow is computed from the equation:

$$Q_p = (484AQ)/(t_p) \tag{6.3}$$

Where: Q_p = the peak flow (ft^3/sec);

A = the watershed area ($miles^2$);

Q = the runoff volume (inches); and

t_p = the time to peak flow (hours).

The two smallest watersheds used in this study, Sonora S-12 and Walnut Gulch W-3, were modeled using the SCS method. Computed peak flows, as well as the information needed to determine peak flows, are listed in Table 6.2.

Due to the small rainfall volumes and a low runoff curve number, the SCS method was unable to predict any streamflow for eight out of nine storm events modeled at watershed W-3. The fact that the method developed in this study did reasonably estimate peak flow from these storm events indicates that such a peak flow estimation method, based on watershed slope and rainfall intensity, may be more condusive to flash flood analysis in arid basins.

Antecedent moisture conditions were present in three of the five storms tested on Sonora Watershed S-12. This condition and the moderate infiltration property of the watershed cover soil was incorporated to determine relatively high runoff curve numbers. Peak flows computed using the SCS method compared well

WATERSHED	AREA (mi^2)	STORM EVENT	TOTAL RAINFALL (in)	TIME TO PEAK FLOW (hr)	ANTECEDENT RAINFALL (in)	ADJUSTED CURVE NUMBER	DIRECT RUNOFF (in)	PEAK FLOW (in/hr)	OBSERVED PEAK FLOW (in/hr)
W-3	3.47	1	1.63	1.42	1.4	61	.05	.026	.052
"	"	2	.78	1.04	0	41	0	0	.038
"	"	3	1.43	.90	0	41	0	0	.064
"	"	4	.63	.93	0	41	0	0	.026
"	"	5	.64	.48	0	41	0	0	.004
"	"	6	1.29	.37	0	41	0	0	.132
"	"	7	1.43	.55	0	41	0	0	.610
"	"	8	.79	1.05	0	41	0	0	.003
"	"	9	1.19	.55	0	41	0	0	.020
S-12	4.38	39	1.96	1.17	5.29	91	1.15	.737	1.203
"	"	40	3.94	2.67	0.50	79	2.05	.576	.850
"	"	41	1.86	2.75	4.10	91	1.00	.273	.283
"	"	42	1.38	2.08	0	61	0	0	.278
"	"	43	2.88	.73	0.20	61	.04	.041	.321

Table 6.2. SCS peak flow determination method data for selected storm events occuring on Walnut Gulch Watershed W-3 and Sonora Watershed S-12.

with actual peak flows and were considerably higher than corresponding peak flows simulated by the cell storage model. In this situation, the success of the SCS method was attributed to its ability to consider antecedent moisture, low infiltration rate soils, and large, less peaked storm hyetographs.

CHAPTER 7

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 Summary of Results and Conclusions

The first objective of the study was to define the unit area concept and to determine the best unit area for use in the calibration method. Factor analysis was employed to determine the most influential hydrologic parameters affecting the simulated peak flow for each tested unit area. The optimum unit area became the constant size cell in the multicelled network of the cell storage model interpretation of the natural watershed.

In all unit areas tested, rainfall intensity was observed to be the most dominant hydrologic factor affecting peak flow. Rainfall intensity was considered to be the principal factor in the calibration method.

Small areas (0.03125 to .125 square miles) should be the best subunits for unit areas in that they would more likely represent the areas of homogeneous hydraulic characteristics. These areas, however, were found to have parameters that individually exhibited minimal influence on the rainfall-runoff relation, and collectively accounted for less total percent variance of the relationship than larger areas.

As unit area size increased hydraulic parameters tended to increase in their apparent effect on peak flow. The 0.5 square mile unit area was selected for calibration for two reasons: 1) tested parameters within the area accounted for the best total percent variance of the rainfall-peak runoff relation, and 2) individual parameters exhibited a sufficiently strong influence on the rainfall-runoff relation to be used as principal factors in the calibration method.

By testing unit areas in series it was determined that principal hydrologic factors do not vary significantly in the magnitude of influence on the rainfall-peak runoff relation with the relative position in series. This conclusion enabled the 0.5 square mile unit area to be used to calibrate a cell for modeling peak flow response at any position in the natural watershed.

The second objective of the study was to apply the peak flow runoff response of the unit area to calibrate an equivalent sized cell by adjusting the cell storage constant of each cell until the hydrograph of the cell storage model best matched the hydrograph of the kinematic cascade model.

The calibration method was completed for both drainage configurations of the 0.5 square mile unit area by combining principal hydraulic factors into one variable, and relating this variable to rainfall intensity to define equivalent cell storage constants (Figures 5.7 and 5.11). For the simple unit area drainage configuration, plane slope and main channel slope were combined to form the PS-MCS number. For the complex unit area, side channel slope and main channel slope were combined to form the SCS-MCS number. Efforts to combine three factors, main channel slope, side channel slope and plane slope, were unsuccessful.

The unit area without rainfall input was also considered. Main channel slope and main channel roughness was combined to form the MCS-MCR number. A set of calibration curves was developed that related flow input to the cell and the MCS-MCR number to cell storage constants (Figure 5.15). Since flow input to downstream cells cannot directly be determined in ungaged watersheds, this method could not be applied to model ungaged watersheds.

Poor comparison between observed and simulated peak flows for various gaged arid and semiarid watersheds indicated that error incurred from the development of the calibration method limit the application of the cell storage model. These limitations are described in Section 7.2.

The presence of antecedent moisture did not increase the amount of disparity between observed and simulated peak flows, as was expected. The lack of spatial rainfall information may have masked any effect of antecedent moisture on the determined rainfall-peak runoff relation.

A more spatially distributed representation of storm rainfall input may have resulted in better comparison between observed and computed flow. No quantitative assessment of the effects of rainfall variability on the peak flow simulations could be determined.

Comparison of the cell storage model to the Soil Conservation Service peak flow determination method indicated that the cell storage model, with the calibration method developed in this study is better suited for the prediction of peak runoff resulting from short duration, high rainfall intensity storms.

7.2 Limitations of Method

As with all models that reduce the complex processes of the natural watershed to descriptive equations, limitations to the general application of the cell storage model and the calibration method exist.

The reliability of synthetic rainfall-runoff data generated by the kinematic cascade model applied as calibration data for the cell model may be questioned. Although designed and calibrated specifically for ephemeral flood flow, the kinematic cascade model is only a complex estimation of the real system. Error inherent in generating the synthetic data are transmitted on to the calibration curves developed in this study.

The calibration method did not include the hydrologic parameters that exhibited only minimal influence on the rainfall-peak runoff relation. The collective influence of these factors, although small, had some effect on the developed relationships.

The exclusion of infiltration parameters from the sensitivity analysis may have had some effect on the calculated factor loadings due to interrelationships between infiltration and certain hydrologic parameters. For example, roughness of the planar elements and channel segments may have shown more influence on peak flow if plane infiltration parameters had been allowed to vary.

Of more importance, constant infiltration parameters would be expected to effect the application of the model to natural watersheds due to the spatial variation of soil characteristics within the watershed subunit.

The sensitivity analysis and calibration method were performed on fixed drainage configurations within each area. Different configurations would generate different output responses and different magnitudes of significance among tested variables. This is evident when comparing the output responses of the simple and complex configurations of the 0.5 square mile unit area. If the natural watershed subunit does not have a drainage pattern similar to the designed unit area, then difference in peak flows would certainly result.

7.3 Recommendations for Future Research

The successful aspects of this investigation, as well as the unresolved limitations, made evident the need for continuing research to better estimate the cell storage constants of the quasi-linear cell storage model. The following recommendations are considered the most pertinent steps to further the work developed in this study.

7.3.1 Inclusion of Infiltration Parameters into the Calibration Method

Initial simulation experiments indicated that infiltration parameters would be principal factors in the design sensitivity analysis. Studies should be conducted to relate some infiltration rate parameter, plus rainfall intensity and any other dominant hydraulic factors, to the cell storage constant. Much work has been attempted on this aspect of the study, but results were unsuccessful and not reported. If such a relationship were developed, then infiltration parameters could be allowed to vary in the sensitivity analysis resulting in possible changes in the determined optimum unit area size, changes in the relative influence of tested parameters on the rainfall-runoff relation, and/or changes in the total percent variance explanation of the rainfall-runoff relation.

It is important to note that spatial variations of infiltration properties in the natural watershed may be accounted for by developing suites of calibration curves for different Horton infiltration parameters. Subsequently, the hydrologic response of differing soil groups could be modeled without considering infiltration parameters in the sensitivity analysis.

By considering hydrologically unique and identifiable soil infiltration areas, similar to the unit-source watershed discussed by Hickok and Osborn (1969), the model would require more detailed input information. This problem could limit the application of the cell storage model, especially in ungaged basins where often little soil infiltration data are available.

7.3.2 Consideration of Leaky Cells

As noted in Chapter 6, cell storage model simulations of peak flows are often quite higher than observed peaks due to large channel transmission losses. If a simplified variable loss rate function was included in each cell, then better simulations of storm flow hydrographs may be attained. Much work has been done along this line, and it is briefly summarized herein.

There are no channels per se in the cascading cells of the watershed modeled by the cell storage model. Consequently, a transmission loss function based on finite channel characteristics is of little use. By simplifying the numerical behavior of the most influential factors affecting potential transmission losses, and incorporating these relationships into a continuity description of input and output within a given cell, channel loss rates can be related to streamflow and, therefore, cell flow. Various methods for relating channel infiltration rates to streamflow rates have been developed by Burkham (1970).

By assuming that the rate of infiltration is proportional to flow depth and flow velocity, cell losses can be related to cell inflow (Q_i) by a simple power function:

$$Q_f = Q_i - (x Q_i^{\,y}) \tag{7.1}$$

Initial simulation experiments have shown that the coefficient and exponent of Equation 7.1 are related primarily to some combination of the channel variables flow width and flow depth. Specific values of the variables x and y can be determined by using the method of least squares for various hydrologic situations if streamflow rates and channel loss rates are known. The kinematic cascade model can be employed to generate such data.

The disadvantage of the described loss function is that two more fitting parameters, x and y, would have to be calibrated, along with the cell storage constant. Perhaps relationships between the three fitting parameters can be developed that would include the determined significant hydrologic factors affecting peak flow. Clearly, more work is needed on this subject.

7.3.3 Consideration of Other Representations of Precipitation Input

More research is needed to determine if some other measure of precipitation input would better estimate the rainfall-peak runoff relation. A 30-minute precipitation intensity was used in this study, and some measure of rainfall intensity seems best considered the type of storms modeled. Rainfall volume, or some combination of rainfall intensity and volume, may better represent the design input.

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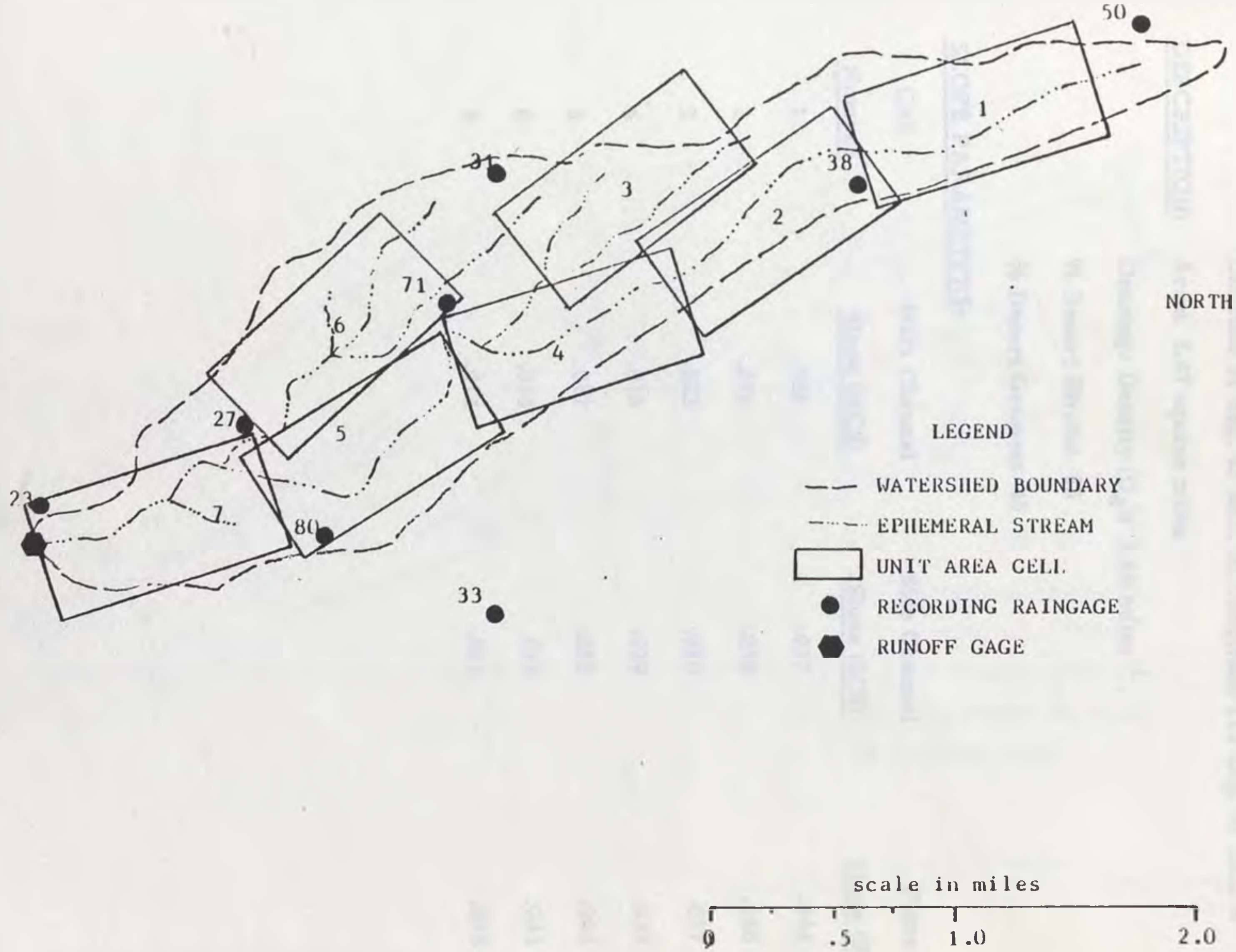
APPENDIX A

DESCRIPTION OF WATERSHEDS USED IN THE VALIDATION OF THE PARAMETRIC STORAGE-ROUTING MODEL CALIBRATION METHOD



WALNUT GULCH WATERSHED W-3

WALNUT GULCH WATERSHED W-3, TOMBSTONE, ARIZONA

LOCATION: Cochise County, Arizona; 1.3 miles northeast of Tombstone

Latitude 31 deg. 43 min. N; Longitude 110 deg. 03 min. W

DESCRIPTION: Area: 3.47 square miles

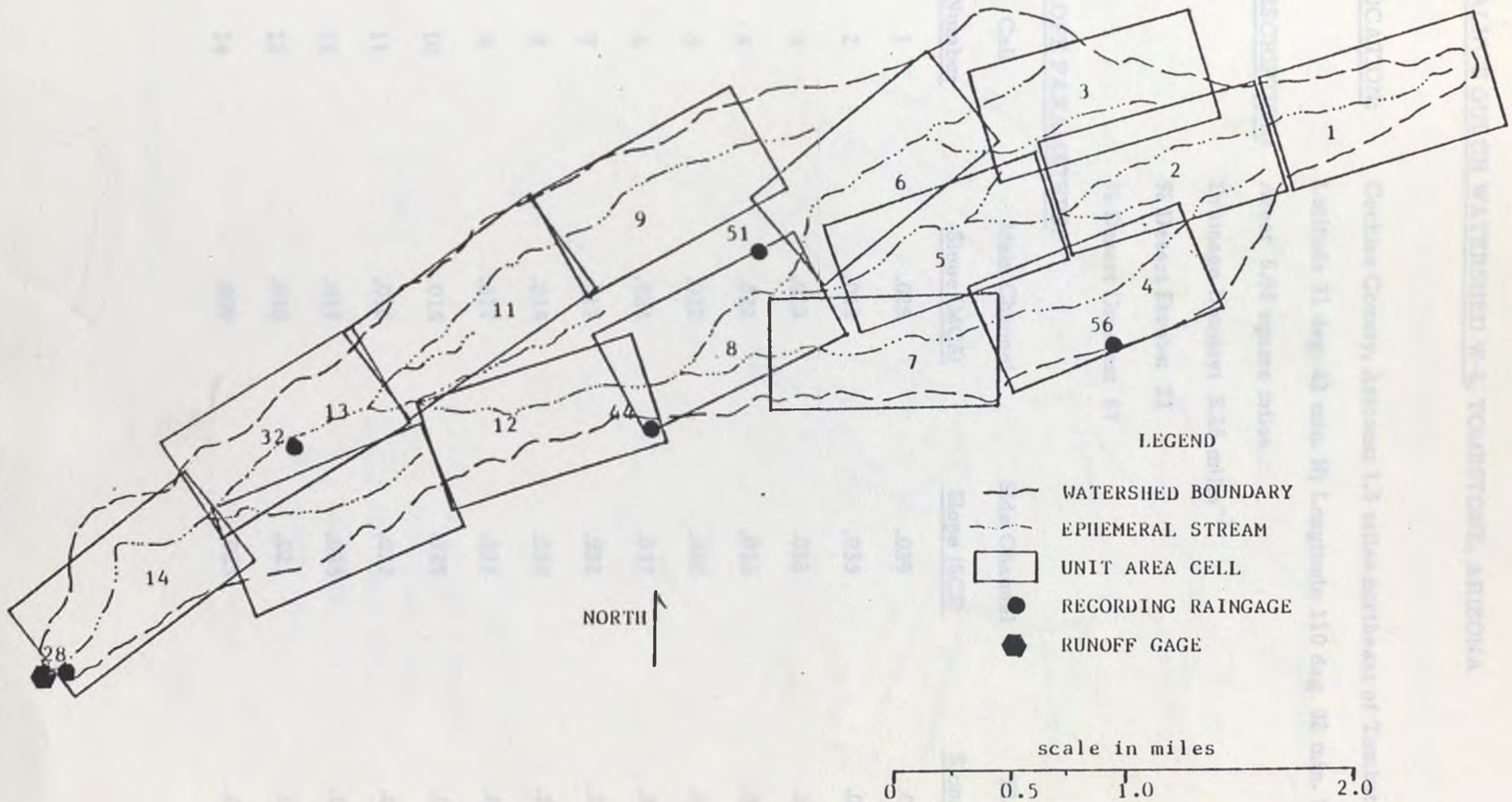
Drainage Density (D_d): 3.65 miles^{-1}

% Desert Shrubs: 55

% Desert Grasses: 45

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.026	.037	.044
2	.025	.038	.046
3	.023	.030	.037
4	.018	.029	.038
5	.017	.035	.045
6	.018	.035	.041
7	.014	.031	.035



WALNUT GULCH WATERSHED W-8

WALNUT GULCH WATERSHED W-8, TOMBSTONE, ARIZONA

LOCATION: Cochise County, Arizona; 1.5 miles northeast of Tombstone.

Latitude 31 deg. 43 min. N; Longitude 110 deg. 02 min. W.

DESCRIPTION: Area: 5.98 square miles

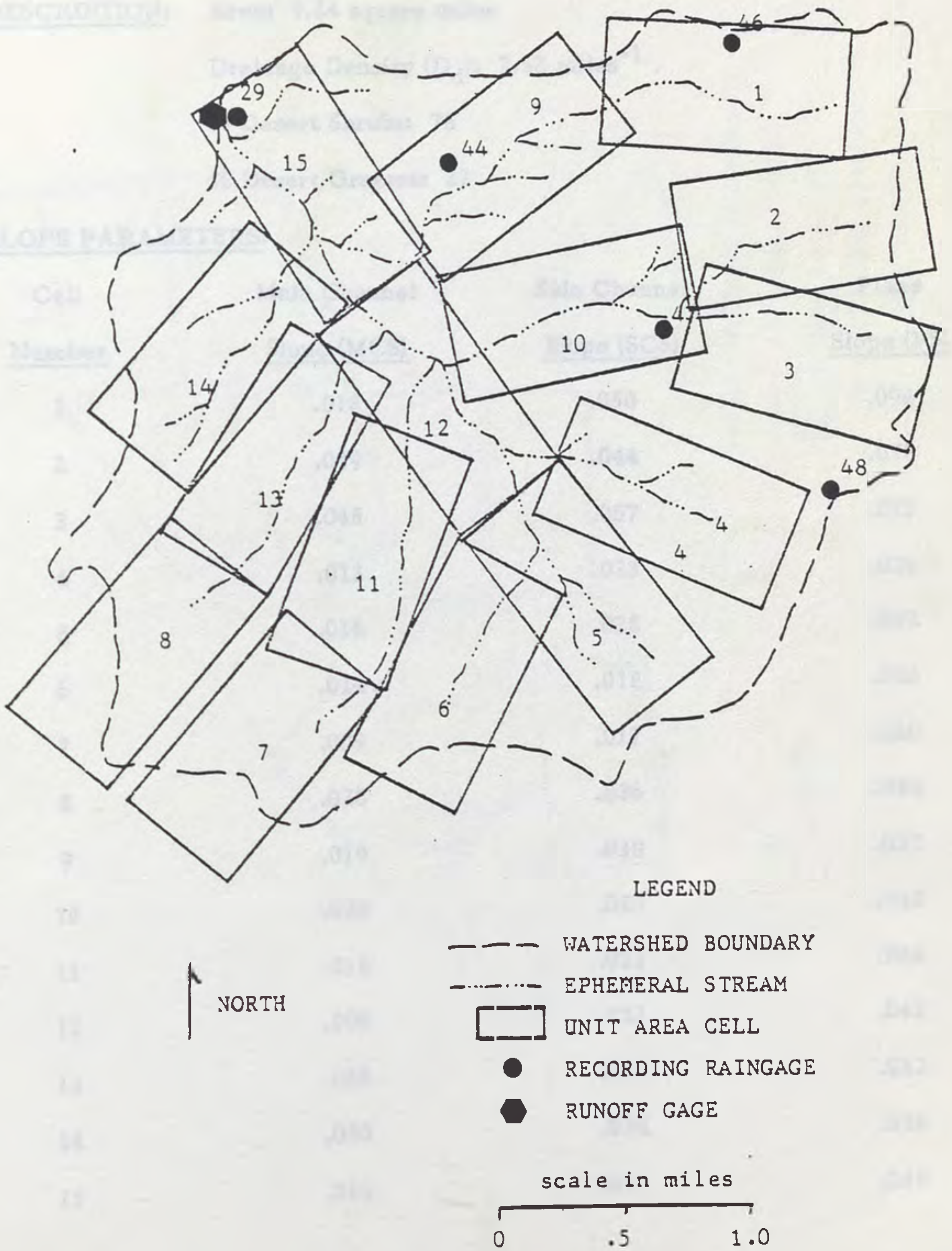
Drainage Density: 3.26 miles^{-1}

% Desert Shrubs: 33

% Desert Grasses: 67

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.025	.039	.054
2	.019	.035	.049
3	.023	.038	.052
4	.022	.036	.057
5	.022	.040	.055
6	.024	.037	.051
7	.017	.032	.052
8	.015	.030	.056
9	.017	.033	.046
10	.015	.029	.047
11	.016	.032	.034
12	.017	.035	.039
13	.010	.021	.043
14	.009	.023	.046



WALNUT GULCH WATERSHED W-15

WALNUT GULCH WATERSHED W-15, TOMBSTONE, ARIZONA

LOCATION: Cochise County, Arizona; .75 miles east of Tombstone.

Latitude 31 deg. 42 min. N; Longitude 110 deg. 02 min. W.

DESCRIPTION: Area: 9.24 square miles

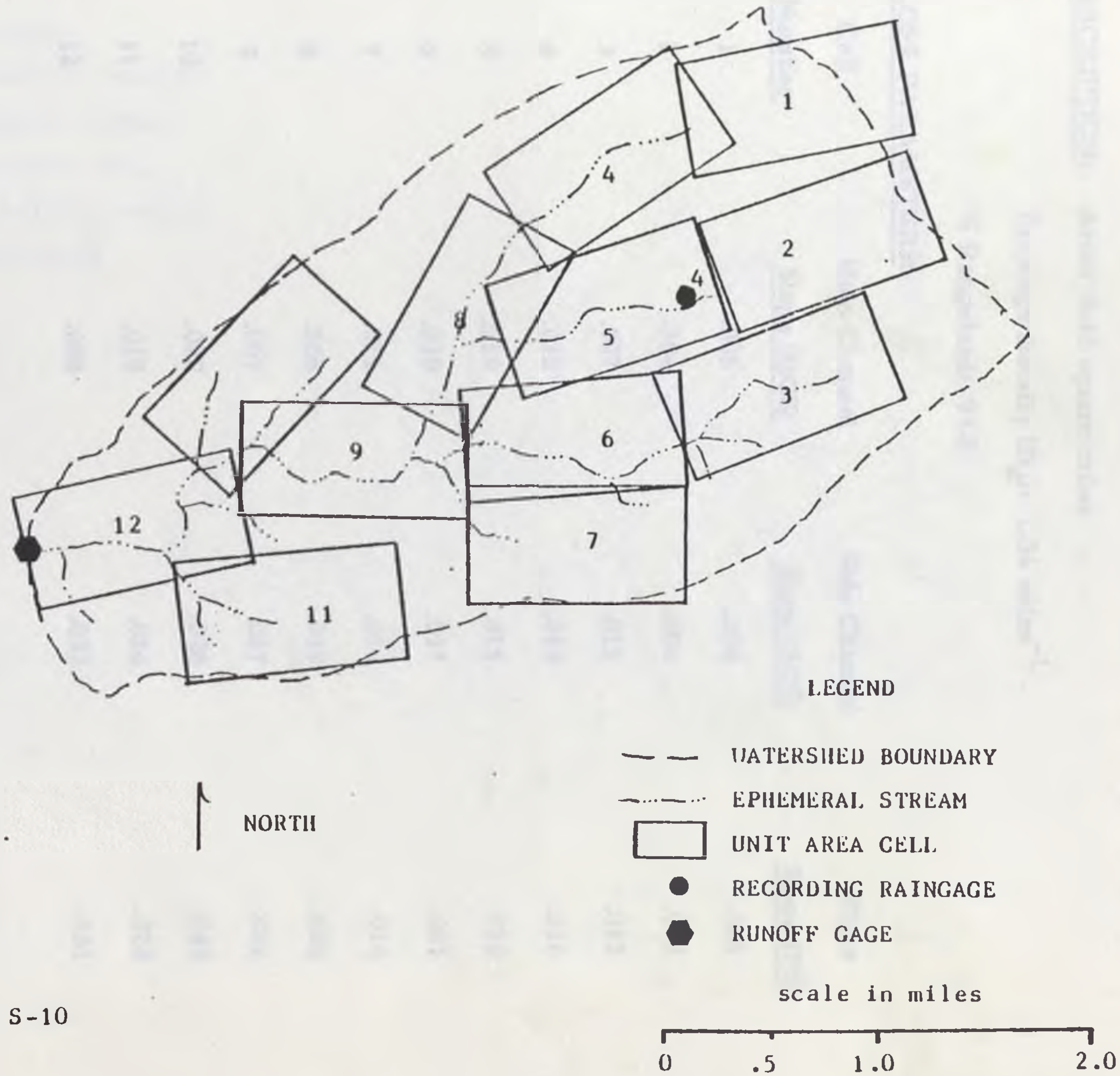
Drainage Density (D_d): 2.52 miles^{-1}

% Desert Shrubs: 78

% Desert Grasses: 22

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.018	.050	.094
2	.019	.044	.078
3	.045	.057	.075
4	.013	.023	.036
5	.016	.028	.037
6	.014	.018	.026
7	.009	.017	.020
8	.028	.036	.040
9	.019	.030	.037
10	.020	.029	.042
11	.018	.021	.024
12	.008	.021	.042
13	.028	.030	.032
14	.030	.034	.038
15	.010	.019	.035



SONORA WATERSHED S-10

SONORA WATERSHED S-10, SONORA, TEXAS

LOCATION: Sutton County, Texas; 6.0 miles northeast of Sonora.

Latitude 30 deg. 37 min. N; Longitude 100 deg. 35 min. W.

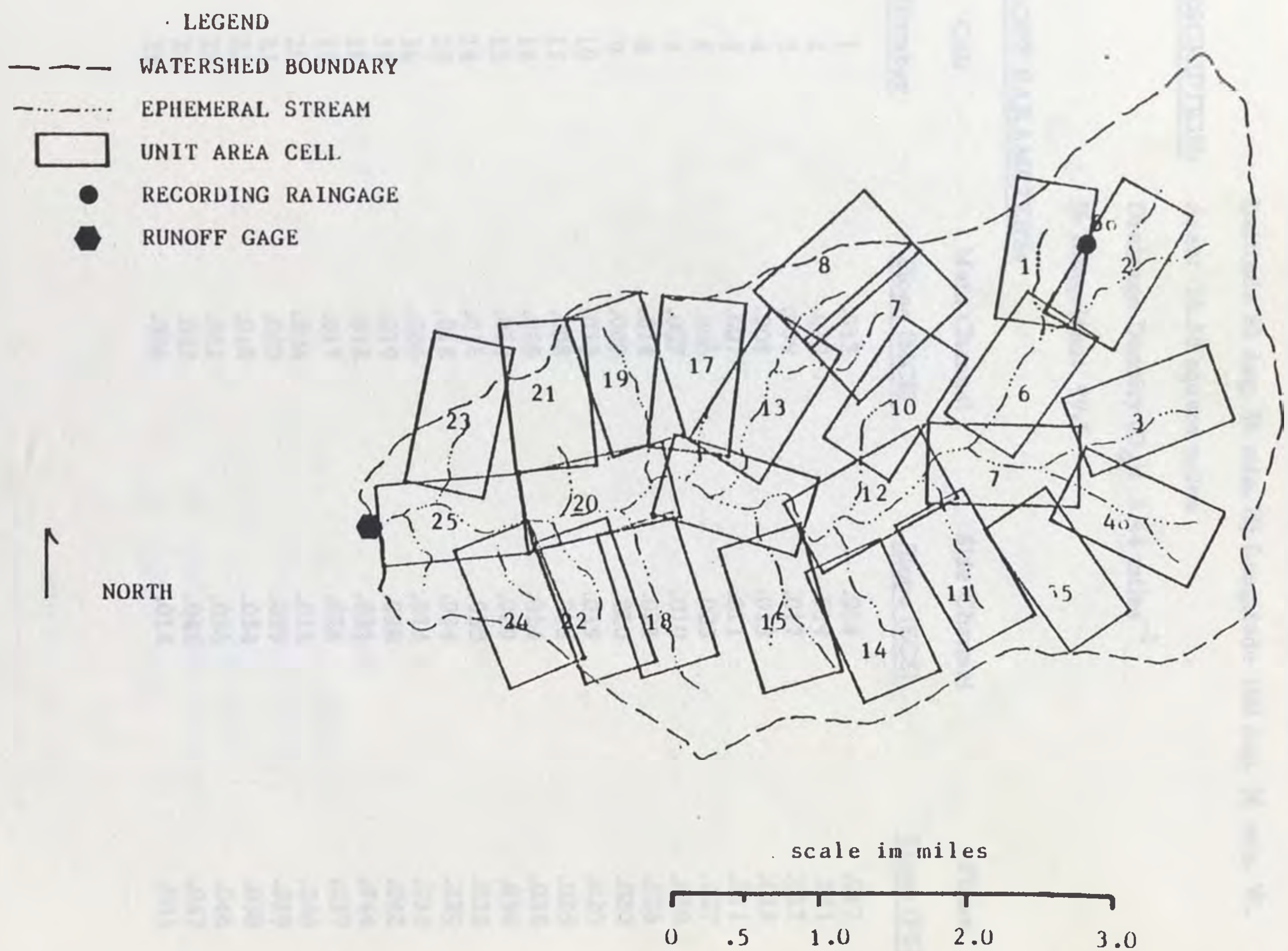
DESCRIPTION: Area: 8.42 square miles

Drainage Density (D_d): 1.34 miles^{-1}

% Rangeland: 99.5

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.005	.004	.005
2	.004	.004	.012
3	.007	.013	.013
4	.010	.015	.016
5	.010	.015	.015
6	.010	.017	.021
7	.011	.014	.014
8	.006	.019	.024
9	.007	.027	.032
10	.020	.026	.042
11	.018	.024	.025
12	.004	.032	.051



SONORA WATERSHED S-11

SONORA WATERSHED S-11, SONORA, TEXAS

LOCATION: Sutton County, Texas; 4.0 miles northeast of Sonora.

Latitude 30 deg. 36 min. N; Longitude 100 deg. 36 min. W.

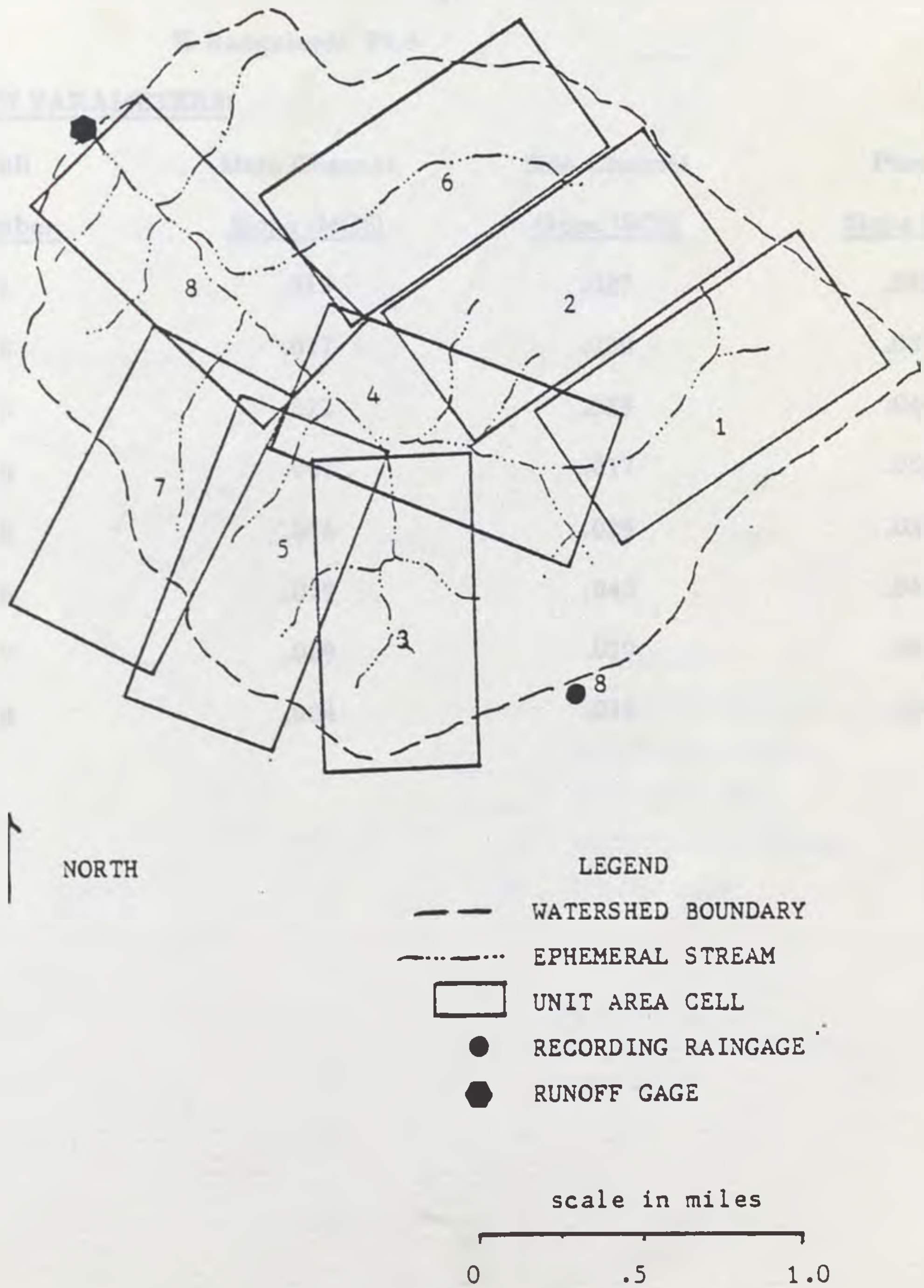
DESCRIPTION: Area: 16.85 square miles

Drainage Density (D_d): 1.44 miles^{-1}

% Rangeland: 99.5

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.013	.018	.017
2	.010	.019	.021
3	.009	.017	.017
4	.008	.013	.018
5	.007	.011	.011
6	.006	.025	.027
7	.007	.010	.020
8	.014	.023	.026
9	.009	.020	.020
10	.013	.019	.020
11	.008	.018	.025
12	.005	.014	.035
13	.010	.029	.036
14	.016	.030	.035
15	.018	.034	.039
16	.005	.014	.035
17	.019	.028	.042
18	.012	.033	.044
19	.017	.028	.039
20	.004	.012	.046
21	.020	.039	.039
22	.018	.034	.038
23	.021	.036	.046
24	.022	.041	.047
25	.006	.014	.031



SONORA WATERSHED S-12

SONORA WATERSHED S-12, SONORA, TEXAS

LOCATION: Sutton County, Texas; 2 miles northeast of Sonora.

Latitude 30 deg. 35 min. N; Longitude 100 deg. 37 min. W.

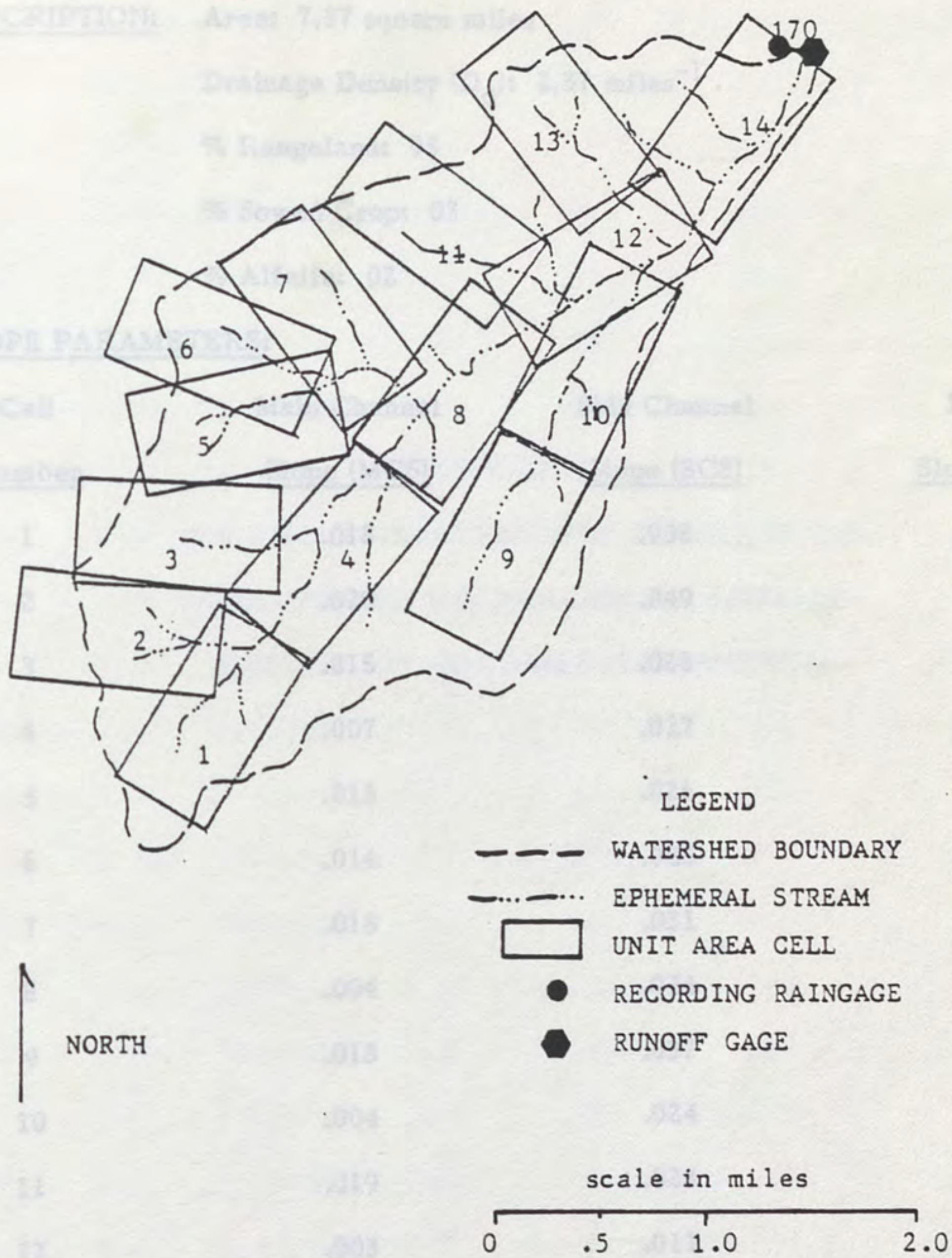
DESCRIPTION: Area: 4.38 square miles

Drainage Density (D_d): 2.10

% Rangeland: 99.5

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.013	.027	.035
2	.017	.030	.037
3	.012	.025	.044
4	.009	.017	.050
5	.016	.029	.039
6	.019	.045	.063
7	.019	.039	.043
8	.004	.012	.044



CHICKASHA WATERSHED C-611

CHICKASHA WATERSHED C-611, ALEX, OKLAHOMA

LOCATION: Grady County, Oklahoma; 5 miles west of Alex.

Latitude 35 deg. 57 min. W; Longitude 97 deg. 51 min. W.

DESCRIPTION: Area: 7.57 square miles

Drainage Density (D_d): 2.57 miles^{-1}

% Rangeland: 95

% Sowed Crop: 03

% Alfalfa: 02

SLOPE PARAMETERS:

Cell Number	Main Channel Slope (MCS)	Side Channel Slope (SCS)	Plane Slope (PS)
1	.018	.038	.043
2	.020	.049	.061
3	.015	.028	.034
4	.007	.027	.041
5	.013	.026	.030
6	.014	.025	.029
7	.018	.031	.040
8	.004	.024	.033
9	.013	.037	.040
10	.004	.024	.029
11	.019	.028	.047
12	.003	.011	.016
13	.022	.027	.039
14	.002	.012	.024

APPENDIX B

DESCRIPTION OF STORM EVENTS USED IN THE VALIDATION OF THE PARAMETRIC STORAGE-ROUTING MODEL CALIBRATION METHOD

APPENDIX B: STORM EVENTS USED IN THE VERIFICATION OF THE PARAMETRIC STORAGE-ROUTING MODEL CALIBRATION METHOD.

Storm No.	Watershed	Date	Reference*	Rain-gage	Observed Peak Runoff (in/hr)	Antecedent Moisture (in)**
	Walnut Gulch					
1	W-03	09-04-65	1216	50	.052	1.40
2	W-03	09-10-67	1226	38	.038	—
3	W-03	08-25-68	1330	27	.064	—
4	W-03	08-31-68	1330	80	.026	—
5	W-03	09-15-69	1370	33	.004	—
6	W-03	09-08-70	1380	23	.132	—
7	W-03	08-10-71	1383	71	.610	—
8	W-03	07-24-72	1412	31	.003	—
9	W-03	09-06-72	1412	23	.020	—
10	W-03	09-27-73	1420	23	.054	—
11	W-08	07-17-65	1216	44	.112	1.25
12	W-08	09-04-65	1216	28	.220	1.02
13	W-08	07-22-64	1194	51	1.110	3.81
14	W-08	08-05-68	1330	90	.147	—
15	W-08	08-31-68	1330	32	.019	—
16	W-08	08-13-69	1370	88	.025	—
17	W-08	07-20-70	1380	56	.113	—
18	W-08	08-10-70	1380	87	.127	—
19	W-08	08-10-71	1383	32	.332	—

Storm No.	Watershed	Date	Reference*	Rain-gage	Observed Peak Runoff (in/hr)	Antecedent Moisture (in)**
20	W-08	07-24-72	1412	32	.050	—
21	W-08	08-21-73	1420	51	.098	.03
22	W-15	09-04-65	1216	29	.111	.85
23	W-15	08-03-67	1262	37	.134	.25
24	W-15	09-10-67	1262	41	.056	.06
25	W-15	08-31-68	1330	47	.178	—
26	W-15	08-16-70	1380	48	.059	—
27	W-15	08-17-70	1380	48	.145	1.64
28	W-15	08-10-71	1383	29	.211	—
29	W-15	07-24-72	1412	29	.020	—
	Sonora					
30	S-10	09-23-64	1262	04	.809	6.22
31	S-10	05-17-65	1262	04	.112	2.50
32	S-10	05-09-68	1330	04	.026	—
33	S-10	08-12-72	1412	04	.279	0.67
34	S-11	09-21-64	1262	06	.095	3.93
35	S-11	09-23-64	1262	06	.391	6.08
36	S-11	05-17-65	1262	06	.310	0.36
37	S-11	05-09-68	1330	06	.132	—
38	S-11	08-12-72	1412	06	.446	0.60
39	S-12	09-23-64	1262	12	1.203	5.29

Storm No.	Watershed	Date	Reference*	Rain-gage	Observed Peak Runoff (in/hr)	Antecedent Moisture (in)**
40	S-12	05-16-65	1262	12	.850	0.50
41	S-12	05-17-65	1262	12	.283	4.10
42	S-12	05-09-68	1330	12	.278	—
43	S-12	10-28-69	1370	12	.321	0.20
	Chickasa					
44	C-611	04-26-63	1370	170	.137	—
45	C-611	05-09-64	1370	170	.493	—
46	C-611	08-07-64	1370	170	.012	—
47	C-611	09-16-64	1370	170	.050	—
48	C-611	10-16-64	1370	170	.124	—
49	C-611	04-10-67	1370	170	.013	—
50	C-611	04-12-67	1370	170	.020	0.92
51	C-611	05-31-68	1370	170	.081	—
52	C-611	07-01-68	1370	170	.100	—
53	C-611	05-06-69	1370	170	.051	—

* Reference: U. S. Department of Agricultural, Agricultural Research Service 1962-1972.

** Antecedent moisture is defined as the summation of the 5 day precipitation before the runoff producing storm.